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THE LIMITING SENSITIVITY OF SEISMIC DETECTORS*

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ABSTRACT

The theory of Brownian motion is applied to the problem of determination of the limiting sensitivity of seismic detectors. It is shown that a certain minimum suspended mass is requird for the recording of small ground motions. Electromagnetic geophones are studied in detail, and it is shown how spontaneous thermal fluctuations in voltage limit the performance of these instruments. Under certain conditions, a geophone may be treated as a power generator, and the necessary suspended mass is then determined by the power requirements of the recording apparatus.

The sensitivity of instruments for the measurement of very small physical quantities is often limited by irregular thermal motion, the Brownian motion, of some of their component parts. The case of galvanometers is the best known, and has been studied in detail both experimentally and theoretically.[1] Similarly, the minimum amplitude of ground motion which can be detected by a mechanical seismograph or an electromagnetic geophone of a given design is limited by the Brownian motion of the mass which is suspended in the instrument.

The purpose of this article is the application of the theory of Brownian motion and of other similar phenomena to the principles of design of seismic detectors, more particularly those employed in geophysical exploration work. It will be shown that the limiting sensitivity of most geophones employed for the recording of reflections is so great that no difficulty should be experienced in detecting motions as small as ground unrest even in quiet locations. Such geophones are, however, designed to respond only to frequencies of the order of 30 cycles/sec. or higher. The problem of detecting small ground motions becomes much more difficult when the frequency is of the order of 1 to 5 cycles/sec., as it may be in long distance refraction work. It is

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[1] Cf. Barnes and Silverman: Reviews of Modern Physics, July, 1934.

in this region that the theory to be presented would be of some value.

The main results, as applied to the usual type of geophone, may be stated as follows: The power which a geophone derives from ground motion is proportional to the product of the suspended mass of the geophone and the square of the amplitude of ground motion; it is, incidentally, also a function of frequency. The average energy of thermal motion of the geophone mass is a function only of the temperature and of the frequency range. It follows that the mass of a geophone must exceed a certain minimum value if a given ground motion is to be registered.

In the first section of this article, the limiting sensitivity of seismic detectors of the displacement and of the velocity types will be deduced from very general principles. In the second section, the particular case of an electromagnetic geophone will be considered from a more practical point of view. It will be shown that thermal fluctuation voltage is one of the important factors which limit the sensitivity of this type of geophone. In the third and concluding section, the geophone is treated as a generator of power which must be furnished the recording apparatus for satisfactory performance.

Only instruments which are critically damped will be discussed; these are the most commonly employed for the registration of earthquakes and in geophysical exploration work.

THE BROWNIAN MOTION OF THE SUSPENDED MASS OF A SEISMIC DETECTOR

The equation of motion of the suspended mass of a critically damped seismic detector can be written

$$\ddot{x} + 2\omega_0\dot{x} + \omega_0^2 x = F/M \tag{1}$$

where x is the displacement relative to the ground, M is the mass, $\omega_0/2\pi = f_0$ is the natural frequency of the seismic detector. F is the force due to ground motion and to other causes; in computations of Brownian motion the force F may, for instance, be the result of molecular motion.

When the force F is due to harmonic ground motion of amplitude A and frequency $\omega/2\pi = f$

$$F = \omega^2 A \tag{2}$$

and it follows from (1)

$$|x| = \frac{\omega^2 A}{\omega^2 + \omega_0^2} \tag{3}$$

and further

$$\overline{x^2} = \frac{1}{2} \frac{\omega^4 A^2}{(\omega^2 + \omega_0^2)^2} \tag{4}$$

and

$$\overline{\dot{x}^2} = \frac{1}{2} \frac{\omega^6 A^2}{(\omega^2 + \omega_0^2)^2} \tag{5}$$

$\overline{x^2}$ and $\overline{\dot{x}^2}$ are respectively the mean square values of the displacement and of the velocity of the suspended mass of the seismic detector.

The irregular thermal motion of the suspended system of the seismic detector can be dealt with according to well-known principles of statistical mechanics. In this case, when the motion is governed by (1), the statement can be made that the mean kinetic energy and the mean potential energy of the suspended mass, which are due to thermal motions, are functions of the absolute temperature of the instrument and can be written as

$$\tfrac{1}{2} M \omega_0^2 \overline{x_B^2} = \tfrac{1}{2} M \overline{\dot{x}_B^2} = \tfrac{1}{2} kT \tag{6}$$

x_B, $\dot{x}_B$ are respectively the Brownian motion displacement and velocity; k is a universal constant ($k = 1.38 \times 10^{-16}$ erg/deg K), T is the absolute temperature in degrees Kelvin.

If the motion of the suspended mass of the seismic detector were recorded without frequency discrimination, it would now be a simple matter to write out the relation for the limiting sensitivity of the seismograph. For, it would only be necessary to state that the mean square motion of the suspended mass, as given by (4) or (5), must exceed the mean square Brownian motion by a factor α which is derived from experience. Practically, however, all types of recorders have some frequency limitation, so that the recorded Brownian motion appears to be smaller than that given by (6). It will be assumed in the following that the frequency discrimination of the recording device is equivalent to that of a low-pass filter with a cut-off frequency $\omega_1/2\pi = f_1$.

The analytic expression for the statement that the mean square motion due to ground acceleration must exceed the mean square Brownian motion by at least the factor α can be written

$$MA^2 \geqq \alpha \frac{2\,kT}{\omega_0^2} \left(\frac{\omega^2 + \omega_0^2}{\omega^2} \right)^2 \cdot G_1 \tag{7}$$

for a displacement type detector, or

$$MA^2 \geqq \alpha \frac{2\,kT}{\omega^2}\left(\frac{\omega^2+\omega_0{}^2}{\omega^2}\right)\cdot G_2 \qquad (7')$$

for velocity recording.

The factors G_1 and G_2 are introduced to take account of the frequency cut-off of the recorder; they are functions of ω_1 and ω_0 of the order of unity, as will be demonstrated.

Experience with galvanometers indicates that a motion of amplitude four or five times greater than the amplitude of Brownian motion can be registered with certainty; it will, accordingly, be assumed in numerical estimates of sensitivity that

$$\alpha = 20$$

since it is proportional to the square of the amplitude.

The equality sign in (7) and (7′) is used when A is identified with the minimum detectable ground motion. Those relations then become equations for the limiting sensitivity of a seismic detector. It is seen that (7), (7′) can be used to obtain the minimum suspended mass of a seismic detector which is to record ground motion of a given amplitude.

The determination of G_1, G_2 requires some consideration of the frequency spectrum of the Brownian motion. For this purpose, let the supposition be made that the motion is different from zero only in some very long time interval τ which must be taken to be much greater than the period to which observations are extended. The force F in (1), which now will be regarded as due to thermal phenomena and which causes Brownian motion, can be represented as a Fourier integral

$$F = \int_{-\infty}^{+\infty} F(\omega)\cdot e^{j\omega t}\cdot d\omega \qquad (8)$$

and, since thermal forces are of random nature, no frequency can predominate, so that

$$|F(\omega)| = \text{const.} \qquad (9)$$

The displacement of the suspended mass of the geophone is obtained from (1)

$$x_B = \int_{-\infty}^{+\infty} \frac{F(\omega)\cdot e^{j\omega t}\cdot d\omega}{\omega_0{}^2 - \omega^2 + 2j\omega\omega_0} \qquad (10)$$

and by Parseval's formula

$$\overline{x_B^2} = \frac{4\pi}{\tau}\int_0^\infty \frac{|F(\omega)|^2 \cdot d\omega}{(\omega^2+\omega_0^2)^2}. \tag{11}$$

Equations (6) and (11) can be used to obtain the value of $|F(\omega)|$ which is constant and can be taken outside the integral sign in (11). It follows

$$|F(\omega)|^2 = \frac{kT}{M\omega_0^2}\,\frac{\tau}{\pi^2}. \tag{12}$$

The effect of the frequency cut-off of the recording device is to change the upper limit in (11) from ∞ to ω_1. Thus, the mean square Brownian motion which is recorded becomes

$$\overline{x_B^2} = \frac{4\,kT}{\pi M\omega_0^2}\int_0^{\omega_1} \frac{d\omega}{(\omega^2+\omega_0^2)^2}. \tag{13}$$

and a simple calculation gives

$$G_1 = \frac{2}{\pi}\left[\tan^{-1}\frac{\omega_1}{\omega_0} + \frac{\omega_0\omega_1}{\omega_0^2+\omega_1^2}\right] \tag{14}$$

as the factor to be used in (7). A similar procedure leads to

$$G_2 = \frac{2}{\pi}\left[\tan^{-1}\frac{\omega_1}{\omega_0} - \frac{\omega_0\omega_1}{\omega_0^2+\omega_1^2}\right] \tag{14'}$$

which is to be used in conjunction with (7').

The relations between mass and minimum detectable ground amplitude established by (7) and (7') are of fundamental importance for seismic detectors; they apply quite generally regardless of the specific design adopted. But the limiting sensitivity which can be derived from those relations is not necessarily attained; under certain circumstances, other phenomena, closely allied to Brownian motion, may lower the useful sensitivity of a seismic detector. This is often the case for an electromagnetic geophone which will be discussed in the next section.

For the purpose of numerical illustration, suppose $f=f_0$, $T=300°\,K$, and $G=1.0$ as an approximation; employing the c.g.s. system of units,

$$MA^2 \geqq 16.7 \times 10^{-14}/f_0^2.$$

The amplitude of ground unrest is generally considered to be of the

order of 10^{-8} cm, so that a seismic detector capable of reaching that level must have a suspended mass

$$M \geqq 1670/f_0^2.$$

An instrument with a period of 1 sec. should have a mass of at least 1670 g. A 10 sec. period seismograph would require a mass of 167,000 g for the same sensitivity. Fortunately, such high sensitivity is not generally desired in a long period instrument; a mass of 10,000 g will give a limiting sensitivity of 4×10^{-8} cm for a 10 sec. period.

THE LIMITING SENSITIVITY AND THE POWER OUTPUT OF AN ELECTROMAGNETIC GEOPHONE

The moving coil electromagnetic geophone consists of a length of conductor capable of motion at right angles to the lines of force of a magnetic field. The ends of the conductor are connected to an amplifier and a recorder; an external resistance is shunted across the moving conductor to provide electromagnetic damping. Let the resistance of the geophone be denoted r, the external resistance R, the magnetic field H, the length of the conductor l. Since the geophone is critically damped

$$l^2H^2/(r+R) = 2\omega_0 M \tag{15}$$

and the equation of motion is the same as (1).

The voltage output of such a geophone is

$$lH\dot{x}\,\frac{R}{r+R}$$

and it follows from (5) and (15) that the mean square voltage can be written

$$\overline{V^2} = \omega_0 M A^2\,\frac{R^2}{r+R}\,\frac{\omega^6}{(\omega^2+\omega_0^2)^2}\,. \tag{16}$$

There are now two fundamental factors which limit the sensitivity of the geophone. One is the Brownian motion of the suspended conductor which was treated in Section 1. The other factor is the spontaneous thermal voltage fluctuation across the resistances r and R in parallel, given by

$$V_N^2 = \frac{2}{\pi}\,kT\omega_1\,\frac{rR}{r+R} \tag{17}$$

where $\omega_1/2\pi$ is the cut-off frequency of the amplifier. The total voltage fluctuation is the sum of (17) and of the fluctuation produced by Brownian motion. As in Section 1, it follows

$$MA^2 \geqq \frac{2\alpha\, kT}{\omega^2}\left(\frac{\omega^2+\omega_0{}^2}{\omega^2}\right)^2 \cdot G_3 \tag{18}$$

with

$$G_3 = \frac{r}{R}\,\frac{\omega_1}{\pi\omega_0} + G_2. \tag{19}$$

The first term on the right-hand side of (19) is the contribution of the thermal fluctuation voltage in the resistor, the second term is due to Brownian motion.

Equations (18) and (19) can also be derived from the fundamental theorem on thermal voltage fluctuations in an arbitrary circuit. This theorem can be stated

$$\overline{V_N{}^2} = \frac{2}{\pi}\; kT \int_0^{\omega_1} \rho(\omega)\cdot d\omega$$

where $\rho(\omega)$ is the resistance component of the impedance of the input circuit of the amplifier which now includes the motional impedance of the geophone.

Since G_3 is always greater than G_2, an electromagnetic geophone has a higher noise level than a mechanical seismograph. This is very pronounced when the cut-off frequency is much greater than the geophone frequency. From this point of view, optical registration is to be preferred whenever extreme sensitivity is desired at low frequencies. Another method to accomplish the same result is to make $R \gg r$.

Substituting

$$\omega = \omega_0 \qquad r = R \qquad T = 300°K$$

and employing the c.g.s. system of units,

$$MA^2 \geqq 5.34 \times 10^{-14}\,\frac{f_1}{f_0{}^3}$$

if the Brownian motion can be neglected ($f_1 \gg f_0$).

For example, let a 5 cycle/sec. geophone be desired which is to be connected to an amplifier with a cut-off frequency of 50 cycles/sec. If the geophone is to detect ground motion amplitudes of 10^{-8} cm, the minimum suspended mass which must be used will be 210 g.

THE GEOPHONE AS A POWER GENERATOR

The most practical approach to the problem of geophone design is through the direct experimental determination of recorder power requirements and computation of geophone power output. For, under ordinary conditions, factors other than Brownian motion and thermal voltage fluctuation limit the useful sensitivity of a geophone. Such factors are, for instance, power line and other electrical pick-up, microphonics in the amplifier, transformer noise. The geophone can then be regarded as a generator which must furnish a certain minimum power to the recording device, e.g., the input circuit of an amplifier.

If the noise level be denoted ϵ, the power to be generated by the geophone is $\alpha\epsilon$. Now, the maximum power which a critically damped geophone can transmit to the recording apparatus is

$$\omega_0 M \frac{\omega^6 A^2}{(\omega^2 + \omega_0^2)^2}$$

because this expression represents the power, derived from ground motion, which is dissipated in the damping device. It follows

$$MA^2 \geqq \alpha\epsilon \frac{1}{\omega_0 \omega^2} \left(\frac{\omega^2 + \omega_0^2}{\omega^2} \right)^2. \qquad (20)$$

An amplifier of the type usually employed in geophysical exploration for the recording of reflections will operate satisfactorily with an input of about 5×10^{-16} watt $= 5 \times 10^{-9}$ erg/sec. (this is equivalent approximately to 25 microvolts across a resistance of 1 megohm). Substituting this value of power for $\alpha\epsilon$ in (20), and assuming $\omega = \omega_0$,

$$MA^2 \geqq 8.1 \times 10^{-11}/f_0^3.$$

Since the frequency of the usual reflection is of the order of 40 cycles/sec., and the amplitude of ground unrest may be taken as 10^{-8} cm, it follows that the suspended mass of a reflection geophone should be greater than 12.5 g, a requirement which is easily satisfied.

INTERPRETATION OF THE TRANSIENT BEHAVIOR OF THE REFLECTION SEISMOGRAPH*

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ABSTRACT

This paper discusses a method of design for the reflection seismograph based on the galvanometer response when the geophone is subject to a unit impulse. A graphical method of obtaining the actual response to an arbitrary geophone motion in terms of the impulsive response is given. A family of desirable types of impulsive response is obtained by analyzing the implications of this graphical computation when strong low and high frequency interference is present. The application of this method of computation to the evaluation of corrections in the apparent arrival time of reflections obtained with different instruments is outlined.

It has been recognized for some years that the performance of the reflection seismograph depends on the overall tuning of the system. This arises from the fact that the motion of the ground at the surface is not due to reflected waves alone but contains other undesirable types of disturbances. The advantages obtained by tuning depend on the fact that the interfering ground motion, which is most frequently caused by wind and surface waves set up by the shot, is composed of either more rapid or more slowly varying oscillations than the ground motion caused by reflected waves. The actual reflected wavelet may contain only two or three oscillations so that its frequency spectrum is fairly broad. Hence we cannot sharply tune the instruments to it as in the case of sinusoidal oscillations. Nevertheless it has been found possible to obtain some separation of the desired waves from the undesired waves by observing the average period of the oscillations in a reflected wavelet. The overall response of the seismograph is then made a maximum to sinusoidal excitation of this period. By experimental adjustment of the rate at which the response falls off on each side of the maximum a balance may be obtained between the degree of objectionable alteration in the character of the reflections by the tuning and the suppression of unwanted disturbance.

The above method of design is based on the steady state behavior of the instruments. Most of the literature on seismograph instruments describes their behavior in terms of their steady state response to sinusoidal excitation. There are two objections to this steady state

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point of view. First, the instruments are characterized by two dependent variables, the amplitude and phase as functions of the frequency of excitation, while the seismogram shows the ground motion as a function of another variable, the time. Second, the relation between the amplitude and phase versus frequency and their effect on the record is too complicated to give more than qualitative assistance to the designer. This difficulty arises because Fourier Integrals are not easy to interpret except for the case where distortion-free reproduction is desired, but here distortion of the true ground motion is the essence of the problem.

The purpose of this paper is to point out certain relations between the appearance of a seismogram and the transient behavior of the instruments to impulsive excitation. These relations may be used as the same type of guide in seismograph design that the frequency response furnishes in audio frequency communication design. The natural tool for treating transient behavior is provided by the operational calculus. However, in many cases where laboratory facilities are available and the cost of experimental equipment is low, a satisfactory design may be developed by 'cut and try' methods in less time than by detailed computation. In this paper a number of useful relations which may be used to guide this type of design will be discussed. The relations are rather elementary to appear at this late date, but the writer has not seen them explicitly discussed in the literature on the seismograph.

The assumption is made that the behavior of a seismograph from geophone to galvanometer is described by a set of linear differential equations with constant coefficients. If a suitable member of the set of differential equations is equated to a time function which has zero value for all times less than the time zero and unit value for all times greater than zero, then the complete solution of the set, giving the galvanometer deflection, will consist of the sum of exponential functions of the time plus a constant. If $A(t)$ is this function, then:

$$\begin{aligned} A(t) &= a_0 + \sum_1^n a_K e^{-\alpha_K t} \qquad t > 0 \\ A(t) &= 0 \qquad\qquad\qquad\qquad t < 0 \end{aligned} \tag{1}$$

a_K or α_K may be real or complex constants. If they are complex they occur in conjugate pairs. The special case solutions for particular values of the constant coefficients do not have physical significance here, because the seismograph components are not measured with

mathematical precision, and so Eq. (1) is in practice completely general.

Now it can be shown that the solution of the original equation in terms of $A(t)$ may be obtained for any type of time function, which is zero for all negative times. A convenient form for this solution is given by[1]

$$i(t) = e(t)A(0) + \int_0^t A'(t - \lambda)e(\lambda)d\lambda \qquad (2)$$

where $A'(t)$ means $(\partial/\partial t)A(t-\lambda)$. The integration parameter λ disappears when the limits are substituted after integration. The proof of Eq. (2) consists in substituting back in the original equation and verifying that the boundary conditions are satisfied. This equation is an analytic statement of the familiar superposition theorem.

For a seismograph of the type ordinarily used in reflection work, $i(t)$ may be conveniently chosen to represent the galvanometer deflection, and $e(t)$ to represent the force acting on the geophone. With this choice of variables $A(t)$ represents the galvanometer deflection due to a suddenly applied unit force on the geophone at the time $t=0$.

Fortunately, the fundamental Eq. (2) contains easily measured quantities. $A(t)$ may be measured with sufficient accuracy for most purposes by suddenly removing a weight from the center of gravity of a shaking table supporting the geophone. For example, a shielded electromagnet may be used to release a small ball. $A'(t)$ may be measured by giving the geophone a sudden change in momentum. In this case a small ball may be bounced on the shaking table. By this simple operation it is possible to obtain the functions $A(t)$ or $A'(t)$, which completely determine the entire system. Consequently, Eq. (2) makes a convenient starting point for the study of the transient behavior of the seismograph.

In Eq. (2) the first term contains the factor $A(0)$ which is the galvanometer deflection at the instant of application of a unit force. This term in seismograph design is usually zero. In the integral, the time appears as the upper limit of integration and as a parameter under the integral sign. This makes the interpretation more complex than the usual definite integral. It should be noted that at each instant of time t, $A'(t-\lambda)$ can only have a value different from zero if $\lambda<t$. $A'(t-\lambda)$ will reduce the integrand to zero wherever $\lambda>t$. Also, as λ increases from zero to t the argument of $A'(t-\lambda)$ decreases so that the

[1] V. Bush: Operational Circuit Analysis. Wiley & Sons, New York, 1929, page 68.

galvanometer deflection $i(t)$ at a time t contains a contribution from the ground motion for all past time. The contribution from past ground motion varies according to the historical weighting function, $A'(t-\lambda)$. For instance the contribution to the deflection from $t=a$ to $t=a+\Delta a$ at the time t is

$$A'(t-a)e(a)\Delta a \tag{3}$$

where Δa is sufficiently small. In order to visualize Eq. (2) more clearly, consider the seismogram in Fig. 1. At (a) we have a single

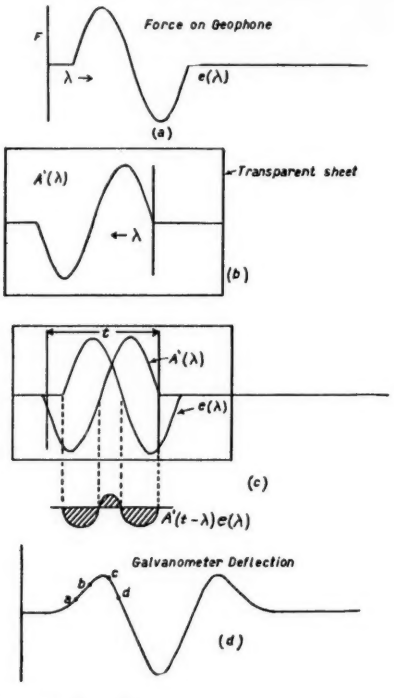

FIG. 1. Graphical computation of:

$$\int_0^t A'(t-\lambda)e(\lambda)d\lambda.$$

The transparent sheet shown at (b) is laid on the curve giving the force on the geophone shown at (a). The corresponding ordinates are then multiplied and the area under the product evaluated as shown at (c). The curve (d) then is plotted for a series of such evaluations made at typical points as *abcd* etc.

trace with an idealized reflection showing the actual force acting on the geophone. At (b) we have a transparent sheet with $A'(\lambda)$ drawn

on it with λ increasing to the left. Now if $A'(\lambda)$ is laid upon the seismogram as at (*c*) and we call the position of the zero axis on the sheet t, and time on the seismogram λ, then obviously the curve on the transparent sheet becomes $A'(t-\lambda)$ when the λ axis is used as a reference. If at (*c*) the ordinates of the corresponding points of the superposed curves are multiplied and the product plotted, the lower curve in (*c*) is obtained. At the time 't' the area under this curve is the galvanometer deflection for the time 't.' The deflection for any other instant of time is computed in a similar manner so that for a sufficient number of such computations as for points *a*, *b*, *c*, *d*, the complete galvanometer deflection may be obtained. The curve (*d*) is the actual galvanometer deflection which is obtained by a seismograph, with an impulsive response $A'(t)$, excited by a ground force $e(t)$. This cinemagraphic

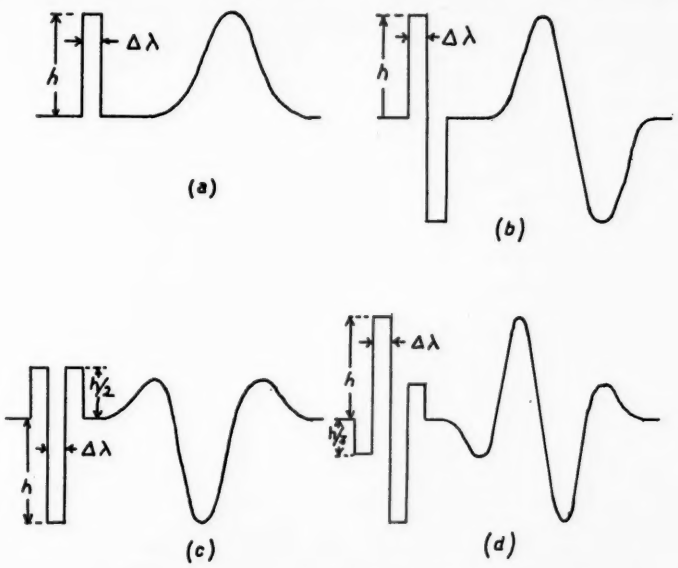

FIG. 2. Basic forms of impulsive response $A'(t)$. The rectangular forms at (*a*), (*b*), (*c*), (*d*), correspond to ideal circuits which, when properly taken to a differential limit, respectively reproduce the force on the geophone or take the first, second and third derivative of the force on the geophone. The smooth forms are physically possible finite equivalents for slowly varying forces on the geophone.

process shows that when $A(o)$ is zero, then $A'(t)$ completely characterizes the system. If various sine waves are plotted as the assumed ground force, the steady state frequency and phase characteristics can be obtained. There are, of course, easier methods for this special case.

The graphical evaluation of Eq. (2) makes it possible to understand several important relations between $A'(t)$ and $e(t)$ which are essential in a well designed seismograph.[2] First, it is clear that two reflected wavelets must be separated by an interval greater than the interval for which $A'(t)$ has appreciable magnitude, in order for the wavelets to appear on the seismogram with an undisturbed interval between them. Obviously, $A'(t)$ should occupy as short an interval as is consistent with other requirements, in order to give high resolving power. This requirement generally eliminates the use of lightly damped circuits or filters with a sharp cut off between the attenuated and pass bands, since in this case $A'(t)$ is unnecessarily of long duration.

Second, consider the case where the ground motion is slowly varying and of long duration compared to $A'(t)$. The result is a seismogram whose character is largely dependent on the number of oscillations in $A'(t)$. In Fig. 2 several idealized forms for $A'(t)$ are shown; beside them there are certain typical forms which, in the limit for sufficiently slow ground movement, are equivalent to the rectangular forms. These equivalent forms for $A'(t)$ might be observed on an oscillograph in connection with a study of different types of electrical networks. Consider an $A'(t)$ of the form shown in Fig. 2(a). In this case $A'(t)$ will reduce the product function to zero everywhere except over a small interval $\Delta\lambda$ long. Assuming $A(0)=0$ (this will be assumed in all cases to follow), Eq. (2) reduces to the form,

$$i(t) = \int_{t-\Delta\lambda}^{t} he(\lambda)d\lambda = e(t)\Delta\lambda h = ae(t) \qquad (4)$$

where $a=h\Delta\lambda$ and $\Delta\lambda$ is sufficiently small. This type of $A'(t)$ merely reproduces the function, that is $i(t)$ and $e(t)$ are proportional. If $\Delta\lambda$ is made large a sort of running average of $e(t)$ is obtained for the galvanometer deflection, $i(t)$. When $A'(t)$ is modified to have the form shown to the right in Fig. 2(a), the running average is weighted. That this modified form for $A'(t)$ gives an attenuation of the higher frequencies for sinusoidal ground motion, can be verified by the method shown in Fig. 1. It is obvious that the high frequency attenuation arises from the averaging brought about by the form of $A'(t)$.

[2] It is implicitly assumed that the seismograph is to operate under conditions of strong interference. The less restricted requirements on $A'(t)$ when only mild interference is present will not be discussed in this paper.

If $A'(t)$ does not start at $t=0$ then $i(t)$ will be delayed or shifted along the time axis.

In Fig. 2(b) there is shown a second type $A'(t)$. In this case another rectangle has been added on the negative side of the axis to the single rectangle of Fig. 2(a). This form of $A'(t)$ will reduce Eq. (2) to the form

$$i(t) = \int_{t-\Delta\lambda}^{t} he(\lambda)d\lambda - \int_{t-2\Delta\lambda}^{t-\Delta\lambda} he(\lambda)d\lambda \qquad (5)$$

$$= h\Delta^2\lambda e'(t) = be'(t) \qquad \text{(approximately)},$$

where $b=h\Delta^2\lambda$ and $\Delta\lambda$ is sufficiently small. For this type of $A'(t)$, $i(t)$ is proportional to the derivative of $e(t)$. Again, if $\Delta\lambda$ is large or $A'(t)$ is suitably modified, the result is some type of running average derivative of $e(t)$ for the galvanometer deflection, $i(t)$. It is obvious that in this case the high and low frequencies will be attenuated when sinusoidal ground motion is present. Since at any instant the average ground motion for a short interval is subtracted from the motion of an adjacent interval, it must be true that for sufficiently slow ground motion the galvanometer deflection becomes small. When the motion is very rapid the galvanometer deflection becomes small because of the averaging process.

This same type analysis can be applied to an $A'(t)$ as shown in Fig. 2(c) or (d). In Fig. 2(c) the $A'(t)$ takes a running average second derivative and in Fig. 2(d) a running average third derivative. Any actual $A'(t)$ which is not a generalization of the types shown may be considered to be built up by a suitable addition of these elementary types. It is possible to generalize from Fig. 2(a) backward to obtain $A'(t)$ functions which integrate $e(t)$.

The relationships between the form of $A'(t)$ and the response of a seismograph to slowly varying ground motion given above, show how the number of oscillations and their form affect the low frequency response.

The curves at a, b, c, d in Fig. 2 taken progressively are obtained by a suitable addition of one half cycle to the preceding curve. Considering the steady state frequency versus amplitude characteristic of the seismograph, it is evident that it is possible to obtain six decibels of attenuation per octave, as a limit, on the low frequency side, for each half cycle after the first in $A'(t)$. No general theorem relating to the number of cycles and the attenuation is possible when circuits

like the Wein bridge are to be included, but the curves of Fig. 2 show what can be done in the case where a steadily falling response on the low frequency side is required. An advantage of this purely transient point of view is apparent when it is considered that by directly measuring $A'(t)$ any undesirable form for $A'(t)$ may be quickly and certainly detected and appropriate design changes made.

Let us consider a third set of relations between $A'(t)$ and the seismogram. If the seismograph is excited by rapidly varying ground motion when compared to the variations in $A'(t)$, then a point of view inverse to that above can be taken. In Eq. (2) and the graphical equivalent given in Fig. 1, $e(\lambda)$ and $A'(t)$ can be interchanged, for by a simple change of variables Eq. (2) becomes

$$i(t) = e(t)A(0) + \int_0^t A'(\lambda)e(t - \lambda)d\lambda. \tag{6}$$

The change in wording necessary to make all that was said in the paragraph above apply to this new case is elementary. The short period disturbances have in (6) become the historical weighting function for $A'(t)$. It is apparent that in order to suppress short period random disturbances, it is necessary to keep the slope or derivatives of $A'(t)$ small. In other words $A'(t)$ must not have any sharp bends and should oscillate as slowly as possible.

The reader is no doubt aware of the fact that there are bridge circuits which will suppress a single sinusoidal wave completely. However, if the bridge will completely suppress a wavelet of short duration it will be in balance at all frequencies, and therefore useless for seismograph tuning. The requirement that the derivative of $A'(t)$ be as small as possible does not give suppression for impulsive excitation of the form shown in Fig. 2(a). There is not much that can be done about this excitation since $A'(t)$ must be such that it will have good response to wavelets of longer period.

The analysis of the tuning requirements up to this point has not completely restricted the $A'(t)$. The form may be varied within limits to make it easy to determine the time of arrival by observing the reflections on the seismogram. The field conditions are so variable that an exact analysis of the relation between $A'(t)$ and the probable error in picking the arrival time of a reflection, would probably involve assumptions that are not constant from one location to another. However, it seems reasonable to assume that the shorter the total duration and the more peaked the envelope of a wavelet, the easier it will be

to determine its time of arrival. It is easy to see that this requirement means that $A'(t)$ should be of short duration and have a peaked envelope. The $A'(t)$ shown in Fig. 2(a) meets this requirement but it does not adequately suppress interference. Since it is assumed here that the problem is to obtain reflections in the presence of quite severe interference, some other functional form from $A'(t)$ must be used. For instance if the sharp corners of the rectangles in Fig. 2(b), (c), (d) are rounded, this requirement of a peaked envelope will be satisfied.

The graphical process of Fig. 1 is quite useful to the designer in estimating the apparent shift in arrival time caused by changes in tuning. It is only necessary to make graphical computations for a few assumed wavelets using the directly measured $A'(t)$. The relation between the times for different cycles on the resultant and on the original wavelet can then be evaluated. If these computations are carried out, it will be found, that if the original wavelet contains 'n' half cycles, that each successive derivative will add one half cycle to the original wavelet. (This follows analytically from Rolle's Theorem when it is applied to functions of the type given by observed wavelets.) The added half cycle cannot be considered to have been added at any point in the wavelet so that in order to adjust the time correction when a circuit change is made it is almost essential that some equivalent of the graphical process of Fig. 1 be used, or that the correction be obtained by comparison of seismograms taken under identical field conditions.

The entire discussion above makes it possible to understand the nature of the more usual compromises necessary to satisfy the reflection seismograph design requirements. The requirements on $A'(t)$ which will enable a seismograph to alter the apparent ground motion so that the arrival time of reflected wavelets may be observed in the presence of both short and long period interference are summarized as follows:

(a) $A'(t)$ should oscillate several times with a short period to suppress slowly varying disturbances.
(b) $A'(t)$ should have appreciable magnitude for only a short interval of time in order to give good separation between reflected wavelets.
(c) The derivatives of $A'(t)$ should be small to suppress short period disturbances.
(d) The envelope of $A'(t)$ should be peaked to make it easy to pick the arrival time.

Naturally these requirements are mutually incompatible. The best

balance between them depends on highly variable field conditions. The nature of the problem is such that it cannot be precisely stated for analytical treatment. However, it has been observed that some member of the family of curves shown in Fig. 2 (to the right of its corresponding rectangular equivalent) will balance the requirements (a), (b), (c), (d) for most field conditions. On the low frequency side the attenuation given by (b), (c), or (d) will increase six decibels per octave for each half cycle added to the reflected wavelet as it appears on the seismogram. This high slope makes it necessary to have only three or four half cycles in $A'(t)$ under most conditions. If the zeros of $A'(t)$ are evenly spaced at about the same interval as the zeros of a reflected wavelet, the derivatives of $A'(t)$ may be made sufficiently small to give good high frequency attenuation. The envelopes are peaked so that the reflections will in turn be peaked. Actual field experience shows that a rather large tolerance to variations from the exact form of $A'(t)$ shown in Fig. 2 is permissible. For instance an $A'(t)$ which has one extra half cycle, which may be of little use because of its long period, will make a deficiency which in the average case is just noticeable.

At this point it would be natural to proceed with a discussion of the type circuits which will approximate the desired forms of $A'(t)$. This problem can be approached by considering the Heaviside expansion theorem of the operational calculus. It is the author's intention to discuss the application of the operational calculus to this problem in a subsequent article.

CURVED PATH METHODS APPLIED TO VERTICALS AND TO WIDE SHOT SPREADS*

MORTON MOTT-SMITH†

ABSTRACT

The ray path-wave front chart and similar methods used for vertical shots are briefly described, and the possibility and the advantages of applying the linear time law to these methods is pointed out. A short method of fitting the linear depth law to the observed velocity is described. The possibility of extending any method applicable to verticals to wide shot spreads is shown, and a method of correcting straight path dips for curvature in the case of verticals is pointed out.

VERTICAL SHOTS

It is not difficult to apply curved path methods to vertical shots, for which the receptors are symmetrically arranged on either side of the shot point. The simplest way to do this is to construct a ray path-wave front chart, such as recently described by Peterson,[1] the essential features of which are shown in Fig. 1.

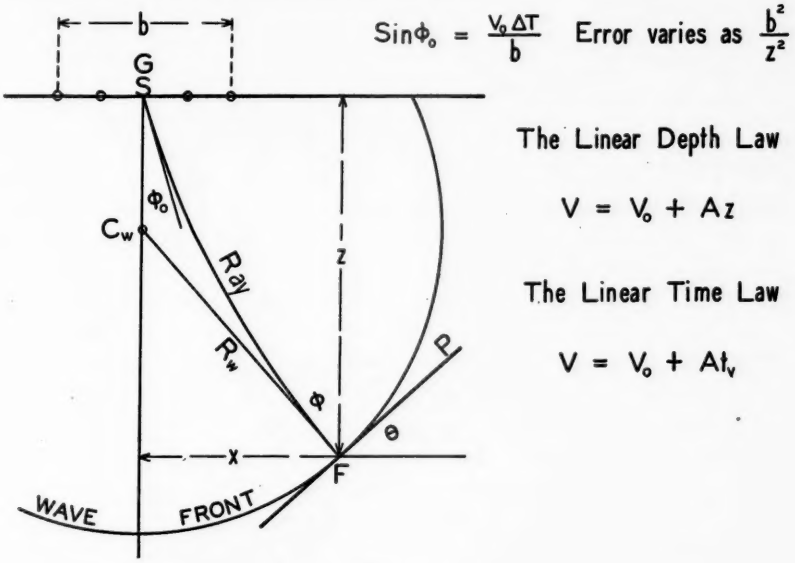

FIG. 1.

* Presented at the Annual Meeting, Houston, Texas, April 2, 1941.

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[1] Raymond A. Peterson: GEOPHYSICS, Vol. 6, No. 1. Jan. 1941.

The path and time equations are usually given in terms of a parameter, $p = \sin \phi / V$, where ϕ is the angle between the ray and the vertical at any point, and V is the velocity at that point. This is constant for any particular ray, hence distinguishes one ray from another. Here it is more convenient to use for this purpose ϕ_0, which is the value of ϕ at S, and will be called the starting angle. Also, since only the terminal points of the rays come into consideration, ϕ (without subscript) will here denote the finishing angle of the ray, such as its value at a reflection point, F. In the parametric equations, then, x, z, and t, are expressed in terms of ϕ_0 and ϕ.

For a vertical shot, the middle or axial ray of those falling on the plane P is reflected directly back to S. The incident and reflected rays coincide. The starting and emergent angles are the same. The former can be obtained by the well-known approximation, $\sin \phi_0 = V_0 \Delta T / b$, where b is the receptor spread. This approximation is very accurate, but the error varies approximately as b^2/z^2. However, if this ratio is large, an approximate correction can be applied. From this formula, the starting angle corresponding to the observed ΔT can be calculated, and thus the appropriate ray selected. Where this ray intersects the wave front corresponding to the observed T, is the reflection point F, whose coordinates x and z can be read directly from the chart.

The plane P that accomplishes the proper reflection must be perpendicular to the ray and therefore tangent to the wave front at F. Consequently the dip angle θ is equal to ϕ. This angle must be calculated from a more or less complicated equation (depending on the velocity law used), so that it is customary to provide a separate chart from which it can be read directly.

If the linear depth law, $V = V_0 + Az$, is used, both the rays and the wave fronts are arcs of circles. The centers of the latter all lie on the z axis. Their positions and the radii can be calculated and the wave fronts put in by compass. Thus C_w is the center, and R_w is the radius of the wave front drawn in Fig. 1. If the centers are marked and numbered on the chart, the plane can be drawn directly on the profile, after the manner of an ordinary dip chart, by simply making it perpendicular to R_w at F. Used in this way, the chart is almost as fast as a straight path dip chart, and is read to the same accuracy.

One advantage of this ray-wave chart is that if constructed for a particular pair of velocity constants, V_0 and A, it can be used for any other pair (belonging to the same velocity law) by merely changing the x, z, and t scales. Or a new chart can be calculated by merely multiplying x, z, and t, by the appropriate factors. The charts are also easy to

calculate and construct. There is in fact nothing easier in the whole realm of curved path operations.

One disadvantage is that if higher accuracy is desired, and sought by increasing the scale, the chart becomes both wide and long and therefore unwieldy. This inconvenience can be avoided by changing the coordinates. Thus if T and ΔT are used in place of x and z, the ΔT axis will be considerably shorter than the T axis. The chart becomes long and narrow and easier to handle.[2] Other variations are possible.

Such charts are much used, but for the most part they are based on the linear depth law—which the author has called the mathematicians delight. However, they all can without much additional computation be constructed for the linear *time* law, $V = V_0 + At_v$, where t_v is the time along a vertical ray. This law, as pointed out by the author in a previous paper,[3] fits a large range of observed velocities much better than the linear depth law does, and moreover can be *closely* fitted to any one of them by the method of least squares. This cannot be done for the linear depth law, because in the average velocity equations the slope constant A appears both algebraically and as part of a logarithm or of an exponent. Consequently these equations can only be solved for A by a method of successive approximation. About the best that can be done in fitting the mathematical curve to the observed average velocity curve is to make it intersect the latter at two chosen points. Thus only two points of the observed velocity are actually used, the others merely aiding in the preliminary smoothing of the curve. For linear time, on the other hand, all of the observed points can be used. A preliminary smoothing is not necessary or even desirable, because the least squaring process does this automatically.

However, for linear depth, it is possible to avoid the difficulties with A by constructing a curve from which A can be obtained for all velocities that can be adequately represented by this law. Such a curve can be calculated directly, that is, without successive approximations. Or, a simple algebraic formula can be set up from which A can be obtained approximately, but with sufficient accuracy. Once A is found, V_0 can be calculated by a direct formula.

In a discussion of the linear time law by Houston,[4] he remarked:

[2] The manner of calculating such a chart is given by J. J. Jakosky, "Exploration Geophysics," p. 490, Los Angeles, 1940.

[3] M. Mott-Smith: GEOPHYSICS, Vol. 4, No. 1. Jan. 1939.

[4] Charles E. Houston, "Seismic Paths, Assuming a Parabolic Increase of Velocity with Depth," GEOPHYSICS: Vol. 4, No. 4, Oct. 1939.

"As Muskat pointed out, because of the transcendental dependence of x and t on the parameter, one cannot obtain $x(t)$ explicitly. The example is of interest however in that the equation of the wave paths can be obtained (in parametric form), the time-distance curve of the direct wave can be computed, and the corresponding reflection time-distance curves can be gotten by graphical methods." This means that a ray-wave chart, and the other charts used for verticals, can be calculated for linear time by direct means, i.e., without approximations. The x equation is to be sure more complicated than for linear depth, but the time equation is much simpler. It contains no logarithms or exponentials.

On the other hand, the linear depth law is not entirely free of transcendental relations. In fact, the time equation is transcendental, and this causes trouble right at the start (where trouble is most discouraging), namely, in fitting the mathematical to the observed velocity curve. It is also the chief trouble maker all the way through. The path is indeed simple, being a circular arc, while for linear time the path is a cycloid.

These two circumstances somewhat offset each other, so that on the whole it is not much more work to compute a chart for linear time than it is for linear depth.

There is in fact a curious analogy between these two velocity laws and those that govern the circular and cycloidal pendulums. For the former, the path is simple and circular, but the time of oscillation is a complicated matter, being given by

$$T = 2\pi\sqrt{L/g}(1 + \sin^2\theta/2^2 + 3^2\sin^4\theta/2^2\cdot 4^2 + 3^2\cdot 5^2\sin^6\theta/2^2\cdot 4^2\cdot 6^2 + \cdots),$$

where L is the length of the pendulum, and θ is the amplitude angle. On the other hand, for the cycloidal pendulum the path is complicated, but the time of oscillation is very simple, being merely $T=4\pi\sqrt{r/g}$, where r is the radius of the rolling circle.

It may be interesting also to point out that the linear time law is identical with the law of falling bodies, while the linear depth law is the alternative which Galileo proposed but rejected, because of its supposed self-contradictory nature. Galileo was wrong about the self-contradiction, but right in another way. His difficulty arose when he attempted to find out what the *average* velocity over a given distance would be—the only thing he could measure. Since this velocity is $\overline{V}=Az/ln(Az/V_0-1)$, it is no wonder that he did not discover it in

the days before the calculus was invented. His reasoning led him to conclude that whatever distance the body had already fallen from rest, it would have used up all of the available time, so that the remainder of the journey would have to be accomplished in just no time —which seemed to him absurd. However, this reasoning is not as wrong as it seems. Had Galileo pursued it a little further—backwards —by making the initial distance traversed smaller and smaller, he would have seen that a body under this law cannot start from rest at all—and this is true. If one puts $V_0 = 0$ in the equation above, the average velocity becomes infinite. However, there is nothing to prevent somebody giving the body a push, after which it can go on precisely as the law requires. Mechanical motions can and do take place in accordance with this law, provided that the body concerned has acquired an initial velocity by some other means.

The same is true for seismic waves. If there is to be a finite average velocity, there must be a finite initial velocity. On the other hand, the linear time law is self-starting. Bodies do fall from rest. For the purposes of a ray-wave chart, however, an initial velocity is necessary in either case, for otherwise all rays start vertically downward at the shot point, and there is no observable quantity there to distinguish one ray from another, or to determine where it will come up. In fact, no physical reason can be given why it should ever come up, or deviate in the slightest (except by reflection) from the vertically downward path on which it started.

For linear time the paths are, as mentioned, cycloids. The wave fronts are oval in shape. A ray-wave chart, as indicated by Houston, can be directly calculated. The reflecting planes are still tangent to the wave fronts at the reflection points, but since the wave fronts are no longer circular, the simple graphical method of determining dips, described for linear depth, can no longer be applied—unless one can draw eye tangents with passable accuracy. However, the oval wave front can be replaced by one or more circular arcs, with sufficient accuracy (except for very small T), and the centers being given, the graphical method can then be applied to this approximate linear time chart.

The other types of charts used for verticals can also be directly computed for the linear time law.

WIDE SHOT SPREADS

The charts for verticals can be used for end shots, and for short spread shots, but the shot length cannot much exceed 1000 feet with-

out the errors becoming excessive. For greater shot lengths, other methods or charts must be used.

The problem of the wide shot spread is much more complicated than that of the vertical shot. Its general fetures are shown in Fig. 2, where X is the shot length, t and t_r are the times along the incident and reflected rays respectively, ρ_0 and ρ are the starting and finishing angles of the reflected ray.

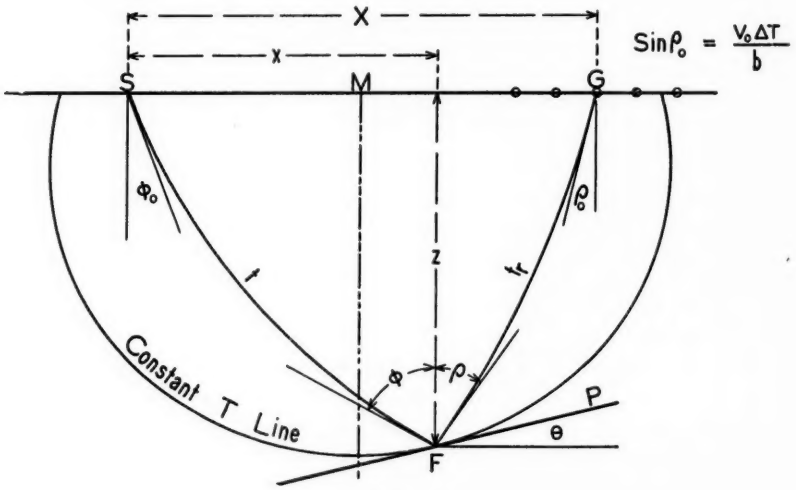

FIG. 2

Integrable equations for t, t_r, x, and z, have been given by Rutherford[5] for a velocity that varies as the square root of the depth, which however, is not quite the same as the linear time law discussed here. It is not difficult to set up such equations, but they are altogether too complicated for practical use. The real problem is to devise a simple approximate method or chart by which results can be obtained quickly and with sufficient accuracy. Also the method of computing the chart must not be too long. The method devised by the author can only be given here in outline.

First, the emergent angle of the reflected ray is computed from $\sin \rho_0 = V_0 \Delta T / b$. A set of rays could then be calculated for specified values of $\sin \rho_0$ or of ΔT, but since they would be identical with those drawn on the vertical chart, it is only necessary to trace the latter on

[5] H. M. Rutherford, "Reflection Dip-Shooting Methods in Seismic Prospecting," Transactions of the American Geophysical Union, Seventeenth Annual Meeting, 1936.

a transparent sheet. This sheet then becomes a movable ray chart, which in use is placed on the profile in such a way that the rays diverge from G.

Second, a separate chart of constant T lines is made for a given X. This can be done by assuming values of t and t_r such that their sum is T, and finding the point of intersection of the corresponding wave fronts, which is F. The locus of these points is the constant T line sought. For linear depth, the equation of this line can be obtained in terms of x and z; but for linear time, each point must be computed by a method of successive approximation.

This is a very long process, but it can be avoided (except as an occasional test may be required), not only for linear depth but for any other usable velocity law, in the following manner. For straight path, as is well known, the constant T line for a given X is an ellipse whose major axis lies in the shot line. For curved path, the constant T line is a complex oval which, however, closely approaches an ellipse. The major axis is still horizontal, but lies below the ground level, and the lengths of the axes are of course different than for straight path. But these quantities can be calculated, and an ellipse, on the same axes substituted for the oval. Or, better still, the ellipse itself can be represented by two circular arcs—a method often used by draughtsmen. This approximation is especially close when, as in the present case, the two axes differ but little in length. The radii and centers of these arcs can be found, and the arcs put in by compass. If the centers are marked and numbered on the chart, they can be used for the graphical determination of dips, precisely as described for the ray-wave chart. Finally, if the dips do not exceed 20 to 30° (the amount depending on circumstances) the major arc alone will suffice, in which case the operation of the chart becomes very simple.

To construct a time line chart like this, it is only necessary to calculate two points on each time line, namely, the positions of F for $\theta=0°$ and for $\theta=90°$, as shown in Fig. 3. These points being special cases, the computations are much simpler than for the general point. If the origin is taken at M, x_{90} is the semi-major axis of the oval, and z_{90} is its depth below the ground. The semi-minor axis is then z_0-z_{90}. J is the point where the two arcs join.

Since an approximation to an approximation has here been made, it might seem that the results should be doubly wrong. Tests have shown, however, that the major arc lies actually closer to the true T line than does the true ellipse. Only along the minor arc, where the dips are very high and therefore unusual, do the two errors add.

Theoretically, a different T line chart is required for each different shot length; but actually the T lines change so little with the shot length that only a few charts are required. The movable ray chart takes care of nearly all the differences caused by a change of shot length. Thus, up to a shot length of 3000 feet, two charts in addition to the one for verticals generally suffice for all the intermediate values

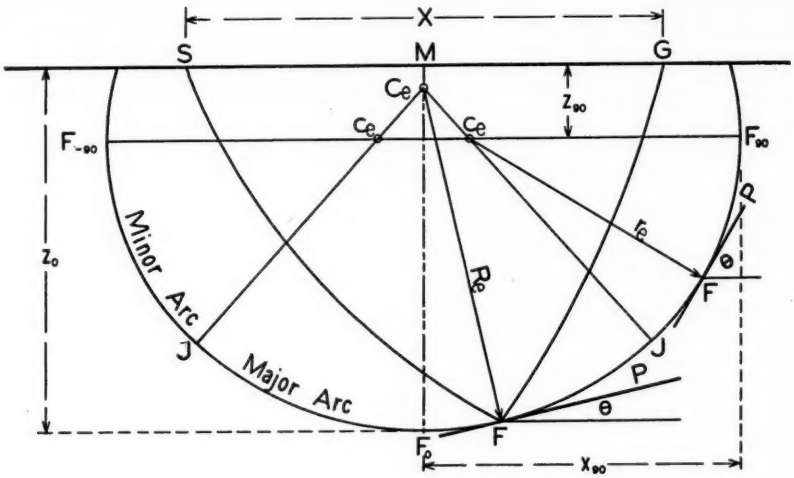

FIG. 3

of X. If only a small range of shot lengths is used, one spread chart will do. Finally, it is possible to specify in advance the maximum allowable depth error, and to determine the values of X for which charts must be made, and therefore the number of them that will meet the specification.

Image or mirror point charts can also be made for curved path. They can in fact be derived from the above described reflection point charts by a graphical method. But for such charts, both the ΔT and the T lines change with X, so that a complete chart—containing both sets of lines—must be made for each required X. The number of charts required for a given accuracy, however, is the same as for the reflection point charts, and the charts once made are used in exactly the same way and with exactly the same speed as straight path charts of the same sort.

In all the methods described above, curved path is applied directly to the determination of dips and depths. When, however, the dips are mild, the differences between straight and curved path methods are

very small, and usually quite negligible. It frequently happens that nearly all the dips of a prospect are mild, only a few of them being steep enough to require a curved path method. In that case, it would be advantageous to have a simple rapid method by which the steep dips could be *corrected* for curvature, while the others are let stand. This would avoid the calculation and use of a more complicated curved path chart for the whole prospect, for the sake of only a few dips that may require it. For purposes of correction only, the fit of the mathematical to the observed velocity does not have to be so good as for the direct use of curved path, because the errors of misfit now affect only the corrections, not the main quantities. Hence the simple linear depth law will suffice. A simple correction formula for the dips has been found, which covers all velocities within the practical range with an error no greater at any point than 5 feet per 1000 feet, and usually much less. For this formula, the slope constant, A, of the linear depth law must be known. But this can easily be found by the simple rapid method already described. V_0 is not needed. So far, however, this formula applies only to vertical shots.

In concluding, the author wishes to thank the Independent Exploration Company for permission to publish this paper.

A NOTE ON A RATIONALIZED VELOCITY DEPTH EQUATION*

NEIL R. SPARKS†

ABSTRACT

An average velocity depth equation of the form $V = V_0(1+aZ)/(1+bZ)$ is suggested and its properties relative to the generalized velocity variation within the sedimentary column are discussed.

The representation of the average velocity as a function of depth by analytic equations has long been used in seismic surveying as a convenient method of simplifying and speeding up routine computations. The simplicity of an equation and the accuracy with which that equation fits the observed data are generally incompatible to a degree which depends upon the form of the equation and the characteristics of the particular set of observed data.

A more or less universal characteristic of the seismic velocity data obtained from velocity determinations in deep wells is that the average velocity increases with depth more rapidly at shallower depths than at the greater depths. The velocities observed from refraction shooting with very long spreads (depth of penetration greater than that of the drill) rarely exceed 20,000 ft./sec. (occasionally 25,000 ft./sec.) within the sedimentary column irrespective of the depth of the column. The corresponding average velocities to these greater depths are, of course, less than this figure.

A rationalized average velocity depth equation to fit these general characteristics would be one which has a specified initial velocity at zero depth, increases with the depth most rapidly at the shallower depths, and approaches but does not exceed a value of the order of 20,000 ft./sec. at the greater depths. An equation of the form, $V = V_0(1+aZ)/(1+bZ)$,[1] possesses these characteristics. When the depth (Z) is zero, the average velocity is V_0. As long as the constant a is greater than b, the rate of increase in velocity with depth will be great-

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† Joint Geophysical Laboratory Stanolind Oil & Gas Company and Western Geophysical Company.

[1] A rectangular hyperbola whose asymptotes are $Z = -1/b$ and $V = V_0a/b$. The instantaneous velocity corresponding to this average equation is $v = V_0(1+aZ)^2/(1+2bZ+abZ^2)$.

est at the shallow depths. When the depth is increased without limit the average velocity monotonically approaches a maximum value of $V_0 a/b$.

The determination of the constants (a, b, and V_0) to fit a set of observational data may be accomplished in several ways. A method found to be convenient and rapid applies equally well either to the velocity-depth or time-depth plot of the data. It consists of choosing three points on the observed curve (V_1, V_2 and V_3 or T_1, T_2 and T_3) such that the corresponding depths (Z_1, Z_2 and Z_3) are in the ratio of 1:2:4 respectively. For this condition the three constants are:

$$V_0 = V_1 \frac{2\left(\frac{V_3-V_2}{V_2-V_1}\right)-\left(\frac{V_3}{V_1}\right)}{2\left(\frac{V_3-V_2}{V_2-V_1}\right)-1} \quad \text{or} \quad = \frac{4Z_1}{T_1} \frac{\left(\frac{2T_2-T_3}{2T_1-T_2}\right)-1}{4\left(\frac{2T_2-T_3}{2T_1-T_2}\right)-\left(\frac{T_3}{T_1}\right)}.$$

$$a = \frac{1}{2Z_1} \frac{2\left(\frac{V_3}{V_1}\right)-\left(\frac{V_3-V_2}{V_2-V_1}\right)}{2\left(\frac{V_3-V_1}{V_2-V_1}\right)-\left(\frac{V_3}{V_1}\right)} \quad \text{or} \quad = \frac{1}{4Z_1} \frac{4-\left(\frac{2T_2-T_3}{2T_1-T_2}\right)}{\left(\frac{2T_2-T_3}{2T_1-T_2}\right)-1}.$$

$$b = \frac{1}{2Z_1} \frac{2-\left(\frac{V_3-V_2}{V_2-V_1}\right)}{2\left(\frac{V_3-V_2}{V_2-V_1}\right)-1} \quad \text{or} \quad = \frac{1}{Z_1} \frac{\left(\frac{T_3}{T_1}\right)-\left(\frac{2T_2-T_3}{2T_1-T_2}\right)}{4\left(\frac{2T_2-T_3}{2T_1-T_2}\right)-\left(\frac{T_3}{T_1}\right)}.$$

THE PRODUCTION OF ELASTIC WAVES BY EXPLOSION PRESSURES. I. THEORY AND EMPIRICAL FIELD OBSERVATIONS*

JOSEPH A. SHARPE†

ABSTRACT

A solution to the problem of the wave motion produced when a pressure of arbitrary form is applied to the interior surface of a spherical cavity in an ideally elastic medium is derived. This solution is shown to be in qualitative agreement with a number of field observations of the effect of shot-point conditions on the characteristics of reflection seismograph recordings.

INTRODUCTION

Of the three physical processes involved in seismic exploration, namely, the initiation of the seismic waves, their propagation, reflection, refraction, and dispersion, and the recording of some function of the motion of the surface, we possess the least satisfactory understanding of the initiation process. This is in spite of the circumstance that it has been recognized from the very beginnings of reflection exploration that the intensity, quality, and characteristics of seismic records are strongly influenced by conditions at the shot point, and despite the fact that a number of empirical observations concerning the generation of seismic waves have accumulated over a long period of field experience.

These empirical observations, which have become a part of the lore of every field operator, are as follows:[1]

1. A given amount of explosive detonated in a clay or water-saturated sand formation results in a greater amplitude of reflected motion than an equal charge detonated in a dense, rigid formation, such as limestone.

2. If a hole is sprung by an initial large charge in order to form a sizable cavity, later small charges will result in a larger amplitude

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† Joint Geophysical Laboratory of the Stanolind Oil and Gas Company and the Western Geophysical Company.

[1] See McReady. GEOPHYSICS, V, 4, pp. 374, 379–381 (1940) and Beers, VI, 1 (1941), pp. 54–55.

of reflected motion than would be produced in the absence of springing.

3. The frequency spectrum of reflected motion is a function of the formation in which the charge is fired: shots fired in the low velocity zone result in very low frequency motion, compared to shots fired below the low velocity zone; shots fired in a rigid material, such as a limestone, result in a much higher frequency motion than shots made in, for example, a shale; in a general way, the high frequency content of reflected motion increases with an increase in shooting depth.

4. The frequency spectrum of reflected motion is a function of charge size, a larger charge having a tendency to increase the proportion of low frequencies in the reflected motion.

5. The amplitude of reflected motion produced by a given quantity of a high speed explosive, such as a dynamite, is considerably greater than that produced by a quantity of a low speed explosive, such as black powder, even when this quantity has been selected such that the maximum pressure attained is the same for both explosives.[2]

That there has been continuing interest in the effects of shot point conditions on reflections records is evidenced by the issued patents which relate to means of controlling the initiation of elastic waves in order to secure reflection records of desired intensity or character. These patents fall into three categories: some aim, through treatment of the shooting cavity, to improve the efficiency of transmission of the explosive energy into the ground;[3] others describe means of selecting that formation as the site of the detonation which is the most likely to produce correlatable records,[4] and still others disclose arrangements which are intended to impart to the ground a motion whose spectrum is rich in the frequency components which are observed in the average recorded reflection.[5]

As part of a long-range program of seismological research, we have investigated the mechanism of the initiation of elastic waves by explosives and the influence on reflection records of conditions at the shot point. This investigation has employed two lines of attack: the mathematical, with the objective of securing a rational picture of the mechanism of the initiation process which would explain as many as

[2] See Nash and Martin, GEOPHYSICS, I, 2, pp. 239–256 (1936), for a discussion of the properties of explosives.

[3] Johnson, U. S. #2,028,286; Weatherby, U. S. #2,049,236; Salvatori, U. S. #2,073,493.

[4] Weatherby, U. S. #2,154,548; Faust, U. S. #2,156,624; Innes, U. S. #2,192,973.

[5] Scherbatskoy, U. S. #2,156,198; Green, U. S. #2,203,140.

possible of the empirical observations which are listed above, and would serve as a guide to experiment; and the experimental. Part I of this paper discusses the analytical investigation, and Part II, to appear in a subsequent issue of this JOURNAL, describes the results of some of the preliminary experiments which were performed.

ANALYSIS

The problem of the generation of elastic waves by explosion pressures is amenable to mathematical analysis only if one makes an idealized statement of the problem, ignoring many factors which are present in actual shooting. I have chosen to state the problem as follows: *Given a spherical cavity of radius* a *within a homogeneous, ideally elastic, infinite medium of density* ρ *and compressional wave velocity* v; *to find the elastic wave motion which results from application of an arbitrary pressure* p(t) *to the interior surface of the cavity.* Fig. 1 illustrates the statement of the problem.

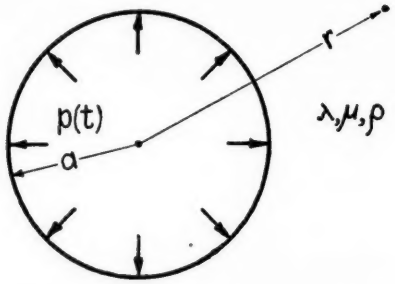

FIG. 1. Illustration of the idealized model of the problem of the generation of elastic waves by explosion pressures.

We should note the extent to which the problem as stated departs from the conditions commonly encountered in practice. The actual site of the explosion, which is a bulbous, water-filled cavity with a cylindrical, water-filled drill hole leading into it, has been replaced by an empty, spherical cavity. This substitution is probably justified: the cross-sectional area of the drill hole is generally small compared to that of the cavity; departure of the cavity from exact sphericity is not likely to produce any essential change in the result; neglect of the presence of the tamping fluid is probably not serious, since experimentally we have found that when an explosive is fired in water, the form of the pressure wave is maintained with increasing distance from the source, and the pressure is inversely proportional to the distance.

By assuming a homogeneous, infinite medium, we have excluded from consideration reflections and refractions at elastic discontinuities near the source. This simplification does not impair the applicability of the analysis, since the only effect of the presence of these surfaces of discontinuity is to add to the primary transient emanating from the source certain other components, delayed in time, and possibly modified in form.

By assuming the cavity to be hollowed out of an ideally elastic medium we have automatically precluded any consideration of the undoubtedly important effects of fracturing, crushing, and compaction of the material surrounding the cavity,[6] and also of the effect of the viscosity and internal resistance of the medium on the form of the wave. The assumption of perfect elasticity is equivalent, in part, to supposing that the cavity is so large, or the charges employed are so small, that the elastic limit of the material surrounding the cavity is never exceeded.

To solve the problem which has been formally stated above we seek an expression for the elastic wave displacement which is a solution of the elastic equation of motion, vanishes at infinity, and satisfies the boundary condition that the stress in the medium must reduce, at the surface of the cavity, to the pressure applied to the interior surface.[7]

The elastic equation of motion is

$$\rho\partial^2\boldsymbol{q}/\partial t^2 = (\lambda + 2\mu)\,\nabla\nabla\cdot\boldsymbol{q} - \mu\,\nabla\times\nabla\times\boldsymbol{q},$$

in which $\boldsymbol{q}$ is the displacement, and λ and μ are the Lamé elastic constants, μ being the rigidity. A solution of this representing compressional wave motion is

$$\boldsymbol{q} = \nabla\Phi, \tag{1}$$

provided the potential Φ satisfies the wave equation

$$\partial^2\Phi/\partial t^2 = v^2\nabla^2\Phi, \tag{2}$$

[6] McReady, *loc. cit.*, discusses the results of these physical changes in the material surrounding the cavity.

[7] Analysis substantially equivalent to that which follows was developed for the discussion of a seismological problem by Kawasumi and Yosiyama, *Earthquake Research Institute of Tokyo Bulletin*, v. 13, pp. 496–503 (1935), and was subsequently utilized by Sezawa, *ibid.*, pp. 741–749, and Sezawa and Kanai, *ibid.*, v. 14, pp. 11–17 (1936). However, due to the limited availability of this publication, the analysis will be outlined here.

where $v=\{(\lambda+2\mu)/\rho\}^{1/2}$ is the velocity of propagation of compressional waves.

Polar coordinates are appropriate to this problem, and since the pressure is to be applied uniformly over the interior surface of the cavity, all motions and stresses will be independent of the angular variables. In view of this, (2), (1), and the boundary condition can be written

$$\partial^2(r\Phi)/\partial t^2 = v^2\partial^2(r\Phi)/\partial r^2; \tag{3}$$

$$u = \partial\Phi/\partial r, \qquad v = 0, \qquad w = 0; \tag{4}$$

and

$$-\left[(\lambda + 2\mu)\partial u/\partial r + 2\lambda u/r\right]_{r=a} = p(t). \tag{5}$$

The only non-vanishing component of the displacement in the elastic wave is u, the radial component. The left side of Eq. 5 is the radial stress in the medium, which must become exactly equal and opposite to the pressure applied to the interior surface of the cavity when the distance is taken equal to the radius of the cavity.

At this point it is convenient to assume $\lambda=\mu$.[8] Rewriting Eq. 5 in accordance with this assumption, and also representing the applied pressure by a Fourier integral, the boundary condition becomes

$$-\rho v^2\left[\partial u/\partial r + 2u/3r\right]_{r=a} = 1/2\pi \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(\gamma)e^{in(\gamma-t)}dn\,d\gamma. \tag{5a}$$

A solution of the wave equation (3) which represents a wave diverging from the surface of the spherical cavity is

$$\Phi = (1/r)e^{-in\tau} \tag{6}$$

in which $\tau=t-(r-a)/v$. The right hand side of Eq. 6 multiplied by any functions independent of r and t is still a solution: consequently

$$\Phi = (1/2\pi r)A(n)p(\gamma)e^{in(\gamma-\tau)}$$

is a solution. Likewise, a sum of such solutions is still a solution, so that

$$\Phi = 1/2\pi r \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(n)p(\gamma)e^{in(\gamma-\tau)}dn\,d\gamma \tag{7}$$

[8] This assumption, which is substantially correct for the material below the low velocity zone, gives a considerable simplification of the analysis which follows, without modifying the final result in any essential way.

is a solution. Forming $u=\partial\Phi/\partial r$ and $\partial u/\partial r$ from Eq. 7, and substituting the resulting expressions into the boundary condition (5a) gives

$$-\rho v^2/2\pi a\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}A(n)\{4/3a^2-4in/3av-n^2/v^2\}p(\gamma)e^{in(\gamma-t)}dn\,d\gamma$$
$$=1/2\pi\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}p(\gamma)e^{in(\gamma-t)}dn\,d\gamma.$$

This is satisfied identically provided the arbitrary function $A(n)$ has the value

$$A(n)=(a/\rho)\{n^2+4inv/3a-4v^2/3a^2\}^{-1}.$$

Substituting this expression for $A(n)$ in Eq. 7 we get

$$\Phi=\frac{a}{2\pi\rho r}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{p(\gamma)e^{in(\gamma-r)}dn\,d\gamma}{n^2+4inv/3a-4v^2/3a^2}. \tag{8}$$

The potential of Eq. 8 satisfies both the wave equation and the boundary condition, and is a *formal* solution to the problem of the wave motion produced when a pressure of arbitrary form is applied to the interior surface of a spherical cavity.

It will be desirable to secure an expression for the wave motion produced by the application of a pressure of unit function form to the interior surface of the cavity, because from this expression the wave motion produced by any other form of pressure application can be calculated conveniently by the use of Duhamel's integral. However, we cannot proceed immediately to let $p(t)$ have unit function form in Eq. 8, since $p(t)$ can have a Fourier integral representation, as in Eq. 5a, only if the integral $\int_{-\infty}^{\infty}|p(t)|\,dt$ exists. Consequently, we shall assume, instead of unit function form, that the applied pressure is described by

$$p(t)=p_0e^{-\alpha t}\quad\text{for}\quad t\geqq 0$$
$$=0\qquad\text{for}\quad t<0$$

in which p_0 is a constant representing the initial, and highest, pressure attained, and α is a positive constant.

Using this form of pressure in Eq. 8, carrying out the γ integration, and factoring the denominator, we have

$$\Phi=\frac{iap_0}{2\pi\rho r}\int_{-\infty}^{\infty}\frac{e^{-inr}dn}{[n+i\alpha][n+2v(i+\sqrt{2})/3a][n+2v(i-\sqrt{2})/3a]}. \tag{9}$$

This integral can be evaluated by the theorem of residues, using for the path of integration the contour shown in Fig. 2. The result is

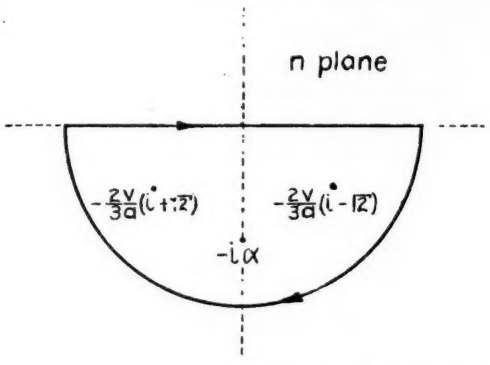

FIG. 2. Contour used in evaluation of the integral of Eq. 9, showing the location of the poles of the integrand.

$$\Phi = \frac{ap_0/\rho r}{(\omega/\sqrt{2}-\alpha)^2+\omega^2}\left[-e^{-\alpha\tau}+e^{-\omega\tau/\sqrt{2}}\left\{(1/\sqrt{2}-\alpha/\omega)\right.\right.$$
$$\left.\left.\sin\omega\tau+\cos\omega\tau\right\}\right] \quad \text{for} \quad \tau \geqq 0, \tag{10}$$
$$= 0 \quad \text{for} \quad \tau < 0,$$

in which we have introduced the abbreviation $\omega \equiv 2\sqrt{2}\, v/3a$.

We now permit α to approach zero,[9] i.e., we permit the applied pressure to take on unit function form, namely $p(t)=p_0$ for $t \geqq 0$, $p(t)=0$ for $t<0$. Then Eq. 10 becomes

$$\Phi = \frac{2ap_0}{3\rho\omega^2 r}\left[-1+\sqrt{\tfrac{3}{2}}\,e^{-\omega\tau/\sqrt{2}}\sin(\omega\tau+\tan^{-1}\sqrt{2})\right] \text{for } \tau \geqq 0, \tag{11}$$
$$= 0 \quad \text{for} \quad \tau < 0.$$

From this we get for the displacement in the medium corresponding to the application of unit function pressure to the interior surface of the cavity

$$u=\frac{\partial\Phi}{\partial r}=\frac{ap_0}{4\mu}\left[\left(\frac{a}{r}\right)^2-\sqrt{\frac{3}{2}}\left(\frac{a}{r}\right)^2 e^{-\omega\tau/\sqrt{2}}\sin(\omega\tau+\tan^{-1}\sqrt{2})\right. \tag{12}$$
$$\left.+\sqrt{2}\left(\frac{a}{r}\right)e^{-\omega\tau/\sqrt{2}}\sin\omega\tau\right] \text{for } \tau \geqq 0, \text{ and } u=0 \text{ for } \tau<0,$$

[9] The justification of this step is the verification, by substitution, that Eq. 11 satisfies the differential equation (3) and the boundary condition (5).

in which we have reintroduced the definitions of ω and μ into the coefficient outside the bracket.

It is to be noted in Eq. 12 that the displacement is made up of three terms, one of which is non-oscillatory and two of which are oscillatory. The non-oscillatory term, which represents the eventual static displacement in the medium, and the first of the oscillatory terms, depend on distance as $(a/r)^2$, whereas the second oscillatory term depends on distance as a/r. Consequently, the displacement at distances more than a few times the radius of the cavity is represented quite adequately by the simple expression

$$u = \frac{a^2 p_0}{2\sqrt{2}\mu r} e^{-\omega\tau/\sqrt{2}} \sin \omega\tau \quad \text{for} \quad \tau \geqq 0$$
$$= 0 \quad \text{for} \quad \tau < 0. \tag{13}$$

Thus, the theory which we have outlined predicts that the displacement in the wave which results from application of a unit function form of pressure to the interior of a spherical cavity in an infinite, homogeneous, ideally elastic medium is a damped sinusoid, with an amplitude directly proportional to the pressure and the area of the cavity, and inversely proportional to the rigidity of the medium. Although the frequency $f = \omega/2\pi = (\sqrt{2}/3\pi)(v/a)$ is directly proportional to the velocity of wave propagation in the medium and inversely proportional to the radius of the cavity, the damping is so high,[10] ($h = 1/\sqrt{3}$, $\epsilon = 9:1$), that the motion is of the nature of a pulse with a duration $\Delta t = (3\pi/2\sqrt{2})(a/v)$.

I have used Duhamel's integral in the form

$$U(\tau) = \frac{d}{d\tau}\int_0^\tau p(n)u(\tau - n)dn,$$

in which $u(\tau)$ is the motion resulting from application of unit function pressure, and $U(\tau)$ is the motion resulting from application of arbitrary pressure $p(t)$, to compute the motion corresponding to the several forms of pressure application which are shown in Fig. 3. In each case the form of the applied pressure as a function of time is shown as a dotted curve, and the displacement of the medium in the resulting wave motion as a solid curve. The maximum pressure at-

[10] When the analysis is carried out without making the assumption $\lambda = \mu$, the damping factor turns out to be $h = [\mu/(\lambda + 2\mu)]^{1/2} = [(\frac{1}{2} - \sigma)/(1 - \sigma)]^{1/2}$, in which σ is Poisson's ratio. For the material of the low velocity zone σ may be as large as 0.4, leading to a damping factor about two-thirds as large as that above, which is still high.

tained is identical in all cases. In Fig. 3-a, the wave motion due to unit function pressure is shown. Fig. 3-b shows the response to pressure of the form $p(t)=p_0(1-e^{-\alpha t})$ for $t\geqq 0$, $p(t)=0$ for $t<0$, where it has been

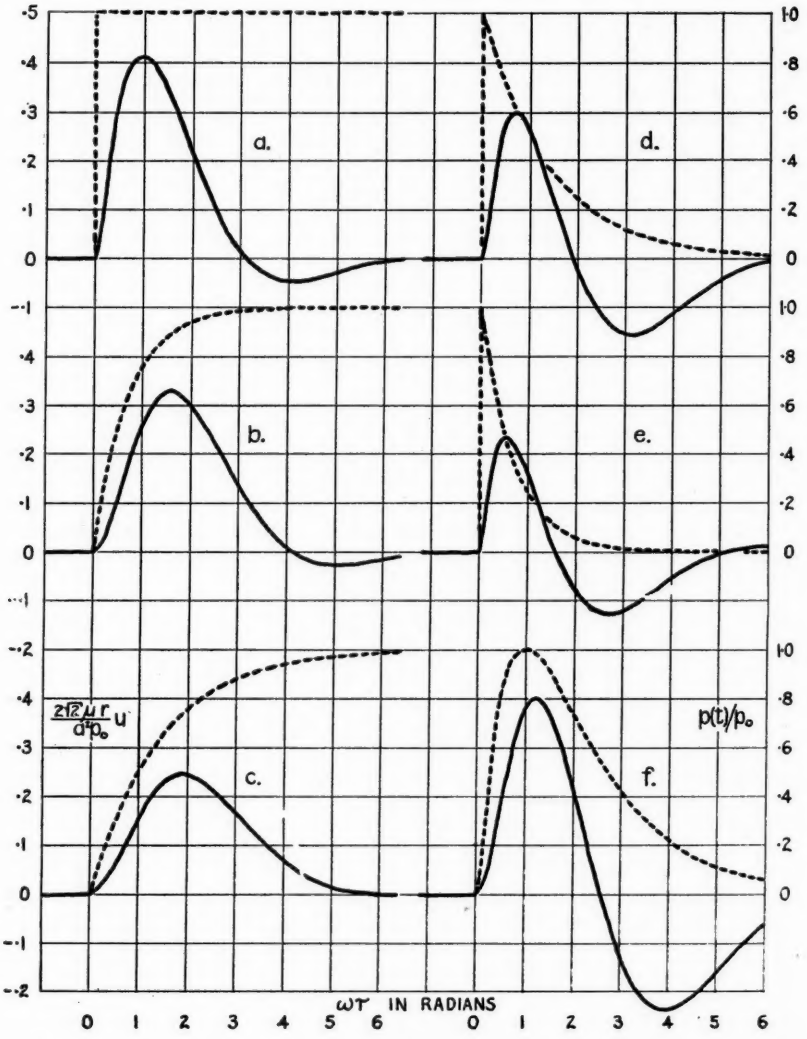

FIG. 3. Displacement in the elastic wave motion (solid lines) produced by the application of various forms of pressure (dotted lines) to the interior surface of a spherical cavity in an elastic medium. Pressures and displacements plotted as functions of ωt and $\omega\tau$, respectively. In all cases $p(t)=0$ for $t<0$. a.) $p(t)=p_0$. b.) $p(t)=p_0(1-e^{-\sqrt{2}\omega t})$. c.) $p(t)=p_0(1-e^{-\omega t/\sqrt{2}})$. d.) $p(t)=p_0 e^{-\omega t/\sqrt{2}}$. e.) $p(t)=p_0 e^{-\sqrt{2}\omega t}$. f.) $p(t)=Np_0(e^{-\omega t/\sqrt{2}}-e^{-\sqrt{2}\omega t})$, in which N normalizes the maximum pressure to p_0.

assumed that $\alpha=\sqrt{2}\omega$. Fig. 3-c is similar, but with a slower pressure build-up corresponding to $\alpha=\omega/\sqrt{2}$. In 3-d, the applied pressure is $p(t)=p_0e^{-\alpha t}$ for $t\geqq 0$, $p(t)=0$ for $t<0$, in which α is assumed to be $=\omega/\sqrt{2}$. Fig. 3-e is similar, but with $\alpha=\sqrt{2}\omega$. Fig. 3-f shows the response to a pressure represented by $p(t)=Np_0(e^{-\alpha t}-e^{-\beta t})$ for $t\geqq 0$, $p(t)=0$ for $t<0$, in which N is a normalizing factor, and α has been taken as $\alpha=\omega/\sqrt{2}$ and β as $\beta=\sqrt{2}\omega$. The pressure assumed in this case probably corresponds quite closely to that which exists in practice.

DISCUSSION

We can now examine the extent to which the predictions of the theory which has been developed agree qualitatively with the empirical observations which were listed in the Introduction.

Eq. 13, or equations derived from it for other choices of the form of pressure application, indicate that the amplitude of the displacement in the elastic wave will be proportional to a^2p_0/μ. Consequently, the displacement produced by shooting in a formation of low rigidity, such as a clay or shale, should be greater than that when shooting in a formation of great rigidity, such as a limestone, which agrees with observation.

It is observed that the preliminary springing of a hole with a large charge results in larger amplitudes of reflected motion being obtained from subsequent small charges than if the cavity had not thus been enlarged. Since the displacement is proportional to a^2p_0, and the pressure wave is propagated in the tamping fluid with its amplitude decreasing inversely as the distance from the charge, we see that the displacement in the medium should be directly proportional to the radius of the shooting cavity,[11] in agreement with this observation.

Comparing Fig. 3-b and 3-c which represent displacements resulting from the application of pressures which gradually increase to a maximum, to Fig. 3-a, representing the displacement resulting from a sudden application of pressure, we see that a powder producing a slow application of pressure should result in a smaller amplitude of wave motion than an explosive producing a rapid application of pressure, which is in agreement with field observation.

According to Eq. 13, an important component in the wave motion resulting from the application of an explosive pressure to the interior surface of a spherical cavity in an elastic medium will have the fre-

[11] Edge and Laby, *Imperial Geophysical Experimental Survey*, p. 205, arrive at the same conclusion through use of an argument similar to the one which I use to explain the effect of charge size on the frequency of the motion.

quency $f=\omega/2\pi=(\sqrt{2}/3\pi)(v/a)$, in addition to the components depending on the particular form of pressure application. This predicts that shots fired in a formation of high rigidity should produce wave motion which is richer in high frequencies than shots fired in a less rigid medium, since not only will the velocity be higher in the more rigid medium, but also the shooting cavity will probably be smaller.

Consider what occurs when a charge is fired at the bottom of a fresh drill-hole. A wave in which the stress greatly exceeds the strength of the material diverges from the site of the explosion, crushing the material as it goes. The stress in the wave rapidly attenuates, however, at a rate which probably is greater than inverse second power, due to the loss of energy by crushing. At some distance from the source which is a function of the strength of the material and the size of the charge which was detonated, the stress will be exactly equal to the strength of the material. At greater distances the material will be "perfectly elastic," except for viscosity and internal friction. This critical distance, which can be called the *radius of the equivalent cavity*, is to be associated with the radius a of the cavity in an ideally elastic medium which enters into the theory which has been developed. We see, then, that a small charge, with which is associated a small equivalent cavity, should result in wave motion which is richer in high frequency components than a large charge, with which is associated an equivalent cavity of larger radius, in accordance with empirical observations of the effect of charge size on the spectrum of reflected motion.

PROBLEMS IN TEMPERATURE CONTROL OF GRAVIMETERS*

DAYTON H. CLEWELL†

ABSTRACT

The theoretical considerations entering into the design of thermostatically controlled ovens for gravimeters are presented. The author points out that to obtain the most uniform temperature distribution without the use of excessive amounts of material, plural thermostat control points on the heater element are desirable. To reduce long-time fluctuations it is recommended that dual thermostating be employed in which an inner controlled-shell is surrounded by an outer thermostated layer held at an approximately constant temperature several degrees lower than the temperature of the inner shell.

INTRODUCTION

The fundamental provision of any gravimeter is a mechanism to translate gravity changes into increments of some directly observable parameter, θ. However, this parameter will be not only a function of gravity, g, but will also be dependent on the mass of the gravity responsive element, the elastic modulus of one or more springs, and various dimensions of the gravimeter. In general we write

$$\theta = f(g, m, k, x^p, y^q, z^r). \tag{1}$$

From this equation the gravity sensitivity of the gravimeter may be defined as S in the equation

$$d\theta = S\frac{dg}{g}, \tag{2}$$

where $d\theta$ is the increment in the observable parameter resulting from the gravity change dg/g. A number of the independent variables in Eq. 1 are likely to be responsive to a change in temperature dT, and a corresponding change in θ will be given by

$$d\theta = S\sum dT. \tag{3}$$

where $\sum$ is the overall temperature coefficient of the instrument. Contemporary gravimeters have a probable error of the order of 0.01 to 0.03 milligals corresponding to significant values of

$$\frac{dg}{g} \cong 2 \times 10^{-8}.$$

* Presented at the Annual Meeting, Houston, Texas, April 2, 1941.

† Magnolia Petroleum Co., Dallas, Texas.

To maintain this order of accuracy it is immediately evident from Eqs. 2 and 3 that $\sum dT \leqq 2\times 10^{-8}$.

If it be assumed that the variables k, x, y and z are temperature responsive and enter Eq. 1 as factors, then

$$\sum = \sigma + p\delta + q\beta + r\gamma \tag{4}$$

if we define σ as the temperature coefficient of the elastic modulus and δ, β and γ as the expansion coefficients of x, y and z respectively. For most materials used in gravimeter construction these temperature coefficients are of the order of 10^{-5}. It is generally possible to arrange for some of the exponents p, q and r, and also some of the temperature coefficients to be negative so that $\sum$ itself is of the order of 10^{-5}. This value of $\sum$ requires, then, that dT be of the order of 2×10^{-3}°C.

It is of course possible to so choose the exponents p, q, and r and the temperature coefficients σ, δ, β and γ in such a way that $\sum = 0$ and one might therefore suppose that dT could be very large; i.e., no temperature control necessary. Although it is possible to adjust $\sum$ to zero it is still necessary to guarantee that all elements of the instrument undergo simultaneous changes in temperature. If, for example, the element x is located at one end of the instrument apart from the other critical elements, it is easily possible for x to undergo a temperature change that may be greater or less than the temperature change of the other end, unless means have been provided to insure a constant distribution of temperature throughout the gravimeter. The usual practice is to use some amount of temperature compensation but the writer has found that even for instruments whose largest dimension is of the order of eight inches, nothing is gained in constancy by reducing $\sum$ to much less than 2 or 3×10^{-6}. To use lower values of $\sum$, so much material of high thermal conductivity must be used in maintaining constant temperature distribution that it seems more practical to use temperature control of dT, at the most, not greater than 10^{-2}, along with temperature compensation. A slowly changing temperature can be easily tolerated since it becomes a part of the instrument drift determined by repeated base-station observations. Depending on the degree of temperature compensation it is sufficient, then, to limit the temperature changes to no more than 0.002 to 0.006°C per hour.

THERMOSTAT THEORY

To consider briefly some of the fundamental characteristics of temperature control, assume a simple thermostated element J in Fig. 1. whose conductivity is k, density is ρ and heat capacity c. For simplic-

ity, let J be a round rod of length l and of unit cross-sectional area, surrounded, except for one end, by a thermal insulating material whose conductivity is very low compared to k. Heat is either subtracted or

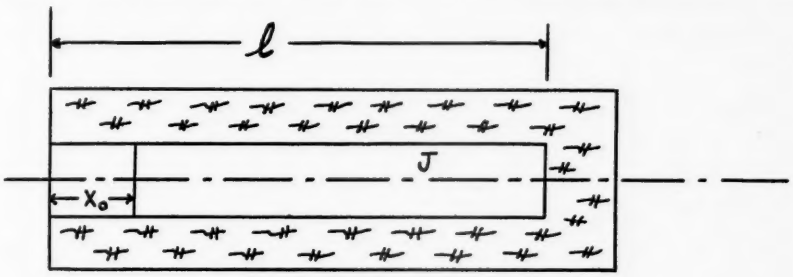

FIG. 1. Single thermostated element.

added to J at its uncovered end. This heat is under the control of a thermostat located a distance x_0 from the end according to the equation

$$Q_{x=0} = -sT_{x=x_0} \tag{5}$$

where x is measured along the axis of J, and Q and T are heat flow and temperature respectively at x at the time t. The symbol s denotes the sensitivity of the thermostat. Eq. 5 states that the thermostat tends to regulate the temperature to the value $T=0$.

Since no heat is generated or lost except at the boundary, the equation of continuity is applicable in the form

$$\Delta^2 T = \frac{c\rho}{k}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2}, \tag{6}$$

and Eq. 5 is the important boundary condition to consider.

A general wave solution of (6) is

$$T = \sum_{a=0}^{\infty}\sum_{b=0}^{\infty} e^{-(a^2-b^2)kt/\rho c}\left[A_{ab}e^{-bx}e^{-2\pi ni(t-x/v)} + B_{ab}e^{bx}e^{-2\pi ni(t-x/-v)}\right] \tag{7}$$

where the frequency $n=abk/\rho c$ and the velocity $v=2bk/\rho c$, $(i=\sqrt{-1})$. The constants a and b are the real and imaginary parts of the complex constant $z=a+ib$ which was introduced on separation of T into two factors involving x and t separately.

The first term in the brackets represents waves (one for each value of z) of frequencies n_a and velocities v_b travelling in the positive x-direction, while the second term represents similar waves travelling

in the opposite direction. At any given time the amplitudes of the waves decrease in their direction of travel showing that they are space attenuated. However, at any given value of x the amplitudes may be decreasing or increasing with time, as the a's are either greater or less than the b's. If we assume x_0 to be small compared to l the backward travelling waves reflected from the right hand end of J can be neglected because of the space attenuation factor. Accordingly, we may, for our simple case set all the B's equal to zero.

The boundary condition, Eq. 5, is applied by equating the coefficient of each term of the series

$$\begin{aligned} -Q_{x=0} &= k\left(\frac{\partial T}{\partial x}\right)_{x=0} \\ &= \sum_{a=0}^{\infty}\sum_{b=0}^{\infty} kA_{ab}(ia-b)e^{-(a^2-b^2)\,kt/\rho c}e^{-2\pi nit} \end{aligned} \tag{8}$$

to each corresponding term of the series

$$sT_{x=x_0} = \sum_{a=0}^{\infty}\sum_{b=0}^{\infty} A_{ab}se^{x_0(ia-b)}e^{-(a^2-b^2)\,kt/\rho c}e^{-2\pi nit} \tag{9}$$

with the result that

$$se^{x_0(ia-b)} = k(ia-b) \tag{10}$$

from which

$$b = -\frac{a}{\tan ax_0}$$

$$s = k\frac{a}{\sin ax_0}e^{-ax_0/\tan ax_0}.$$

Since neither a nor b may be negative, s cannot be less than $\pi k/2x_0$. If the sensitivity is less than this critical value, Eq. 7 degenerates into the usual form of

$$T = \sum_{a=0}^{\infty} e^{-a^2kt/\rho c}(p\cos ax + q\sin ax) \tag{11}$$

and the solution is no longer of an oscillatory nature.

Going to higher thermostat sensitivities we find that for $\pi k/2x_0 < s < 5\pi k/2x_0$ there is but one set of values for a and b, and b is always less than a. This corresponds to a single time-damped wave and after

a short time T reaches a steady state value. In fact $b<a$ until the sensitivity reaches the critical value of $s=35k/x_0$; a condition when $b=a$, and persistent oscillations occur because of the absence of time damping. However, as long as $s>5\pi k/2x_0$ there are two sets of values for a and b, the second set corresponding to a time-damped wave of higher frequency than the fundamental. When the fundamental wave becomes self-sustaining ($s=35k/x_0$) this second wave is still time damped, and it becomes self sustaining only when the sensitivity is raised to $s=141k/x_0$. Now, however, $b>a$ for the fundamental and the amplitude of the fundamental increases with time, limited only by the physical capacity of the heat source. The physical limitations of the heat source cause the average sensitivity to drop to the critical value of $s=35k/x_0$, the harmonic wave damps to zero and we are left with only a self-sustaining fundamental; i.e., $b=a$. Thus the final expression for the temperature, after sufficient elapse of time to remove transients, is found to be either a steady state value for $s<35k/x_0$ or an oscillatory solution whose amplitude is a function of x only, if $s\geqq 35k/x_0$. Whence

$$T = Ae^{-x\sqrt{\pi\rho cn/k}}\ e^{-2\pi ni(t-x/v)}. \tag{12}$$

Since b must equal a for a steady oscillatory solution; Eq. 10 requires $b=a=3\pi/4x_0$ from which the frequency of the wave in Eq. 12 is found to be

$$n = \frac{1.75k}{\rho c x_0^2}. \tag{13}$$

Another important feature of Eq. 12 is the space attenuation factor. The ratio by which the amplitude of a temperature wave of frequency n is decreased as it passes through a material of thickness x is

$$\frac{T_x}{T_0} = e^{-x\sqrt{\pi\rho cn/k}}, \tag{14}$$

a well known relation (1).*

Eq. 8 states that the amplitude of the heat flow at $x=0$ is $Aak\sqrt{2}$ and since this must equal Q_m, the maximum output of the heat source, in the case of self-sustained oscillations is

$$A = \frac{Q_m}{ak\sqrt{2}} = \frac{Q_m}{\sqrt{2\pi\rho ckn}}, \tag{15}$$

* Refer to Bibliography at end of article.

showing that the amplitude, A, of the temperature oscillations decreases with increasing frequency; a very desirable characteristic.

This simple thermostated element has been sufficient to demonstrate the fundamental nature of thermostat action, especially for the case of high-sensitivity control where a steady state solution is impossible unless, by placing the thermostat in close thermal contact with the heat source, one can make x_0 so small that $s < 35k/x_0$. These characteristic features have been demonstrated both experimentally and analytically by L. B. Turner (2) in England.

In the construction of any constant temperature chamber it should be realized that absolute constancy is impossible because for every change in the ambient temperature there is a corresponding small but finite change within the chamber. If the source of heat for the chamber is electrical, fluctuations in the supply voltage will also produce changes within the chamber. Let T be the inside temperature of the oven, ϕ the ambient temperature and V the voltage applied to the heating coils. The heat flow Q through the oven wall per unit area will be

$$Q = C(T - \phi), \tag{16}$$

where C is the conductivity of the oven wall. Thus $dQ = C(dT - d\phi)$. Variations in Q are a result of thermostat action as well as variations in supply voltage so that

$$dQ = \frac{\partial Q}{\partial T}\, dT + \frac{\partial Q}{\partial V}\, dV. \tag{17}$$

Eq. 5 shows that $\partial Q/\partial T = -s$ and since the heat generated by a resistance is proportional to the square of the voltage, $\partial Q/\partial V = 2Q/V$. Making the substitutions we have finally

$$dT = \frac{C}{C + s}\left[d\phi + 2(T - \phi)\frac{dV}{V} \right]. \tag{18}$$

As long as s is large compared to C the variations inside the oven are of course very small, but s would need to be infinite for $dT = 0$. This argument is based on the assumption that the thermostat has continuous control of the heat supply, Eq. 5. The argument is also true for relay-type thermostats which have on-off control. With relay-type control the thermostat is characterized by a certain temperature backlash $(T_H - T_L)$ through which the temperature must oscillate.

If Q_m is the available supply of heat the thermostat cycle will be symmetrical when $Q/Q_m=\frac{1}{2}$, and the amount by which the temperature T overshoots T_H is equal to the amount it undershoots T_L. If, however, $T-\phi$ increases so that the heat must be on for a considerably longer time than it is off, the amount of undershoot will exceed the amount of overshoot and the mean operating temperature of the thermostat drops below the symmetrical value of $(T_H-T_L)/2$.

It has been experimentally demonstrated by Turner (3) that continuous thermostat control is practically indistinguishable from relay-type control, when dealing with the very high thermostat sensitivities that would put the former in the oscillatory region of operation; even

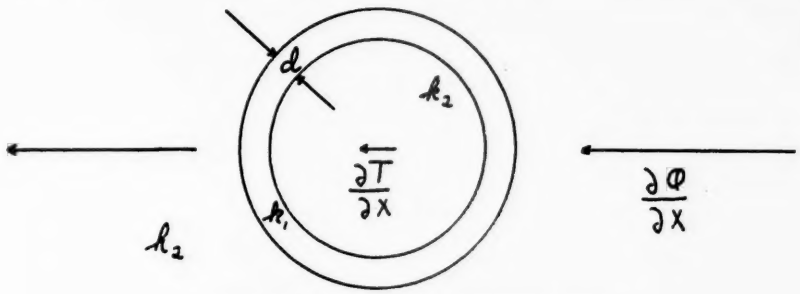

FIG. 2. Shielding effect of a cylindrical shell.

the respective frequencies of oscillation are equal. The Turner reference is suggested as an excellent account of the details of a precision isothermal chamber for laboratory operation.

TEMPERATURE DISTRIBUTION

In order that temperature compensation may be employed in the construction of a gravimeter it is essential that the temperature distribution throughout the thermal housing be maintained as uniform as possible. If an ambient temperature gradient exists there will be a corresponding temperature gradient within the housing. The problem is to make the ratio of the latter to the former as small as possible.

Fig. 2 shows a long cylindrical shell of high conductivity k_1, immersed in a medium of low conductivity k_2, in which medium there exists a temperature gradient $\partial\phi/\partial x$ perpendicular to the axis of the cylinder. La Place's equation is applicable since no heat is generated

or lost and we are interested only in the steady-state solution. This problem is identical with the problem of magnetic shielding where k_1/k_2 is analogous to the relative permeability. The shielding factor of a single shell as represented in Fig. 2 turns out (4) to be

$$F = \frac{\dfrac{\partial \phi}{\partial x}}{\dfrac{\partial T}{\partial x}} = \frac{k_1}{4k_2} \cdot \frac{d}{D}$$

where d is the thickness of the shell and $D \gg d$ is the mean diameter of the cylindrical shell. The ratio k_1/k_2 may be as high as 10^4.

As might be expected from experience with magnetic shielding, a more efficient distribution of temperature with a given weight of high conductivity metal is obtained by dividing the metal into a series of concentric shells. Wills (5) has shown that the most efficient use of material is produced if the ratio of the thickness of the shell (including the shells of low conductivity as well as those of high conductivity) to its mean diameter is the same for all the shells of the concentric assembly. In this case the shielding factor for two high conductivity shells is

$$F = \frac{\mu}{4}\left(1 - q^2 + \frac{\mu}{4} n^3\right) + 1$$

where q equals the square of the ratio of the inside radius to the outside radius for both high and low conductivity shells, n is equal to $1-q$ and μ is the ratio of high to low conductivity of the alternating shells.

A convenient formula for the shielding factor of multiple concentric shells has been developed by Walker and Sterne (6, 7). Assuming all the high permeable shells to be of the same thickness, t_h, and of approximately the same mean radius, R, and all the low permeable shells to be of thickness, t_e, two constants e_1 and e_2 are defined as

$$e_1 = \frac{t_h}{R} - \frac{1}{2}\left(\frac{t_h}{R}\right)^2,$$

$$e_2 = \frac{t_e}{R} - \frac{1}{2}\left(\frac{t_e}{R}\right)^2.$$

Other constants are defined as

$$\alpha = 1 - e_1 - e_2 + \mu e_1 e_2,$$
$$\beta = e_2,$$
$$\gamma = \mu e_1,$$
$$\delta = 1 - e_1 - e_2.$$

The shielding factor is then

$$F = P(x_1)^{n+1} + Q(x_2)^{n+1},$$

where x_1 and x_2 are the roots of the equation

$$x^2 - (\alpha + \delta)x + (\alpha\delta - \beta\gamma) = 0.$$

P and Q are found from a solution of the two simultaneous equations

$$Px_1 + Qx_2 = 1,$$
$$Px_1^2 + Qx_2^2 = 1/2(\alpha + \beta + \gamma + \delta),$$

and n is the number of high conductivity shells.

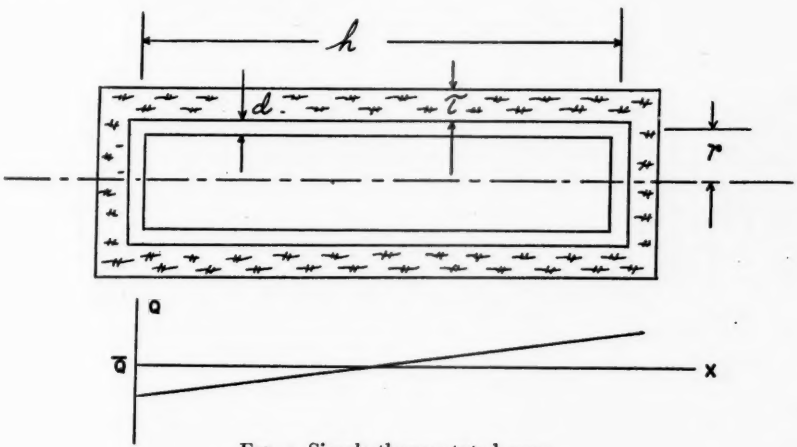

FIG. 3. Simple thermostated oven.

The discussion of shielding against temperature gradients has so far been concerned only with metal cylinders in the absence of sources of heat. In the construction of a gravity-meter thermal oven, it is desirable to wind the heating coil on one of the high conductivity chambers. Such a case is represented in Fig. 3 where a cylindrical metal

box, closed at both ends and having a wall d cm thick, is surrounded by an insulating material of thickness τ. The ratio of thermal conductivities is again equal to μ. Assume that the thermostat is located in the wall of the cylinder a distance $h/2$ from either end. Also assume that a temperature gradient exists on the outside of the chamber parallel to the axis of the cylinder and equal to $\Delta\phi/h$ where $\Delta\phi$ is the difference in ambient temperature between the two ends. If a uniform winding of resistance wire covers the area of the metal cylinder, the thermostat will so regulate the flow of current in the wire that the heat generated per unit area will be constant everywhere on the surface of the cylinder and its end plates. If this constant is denoted by c' watts/cm^2 the action of the thermostat provides that

$$c' = \frac{T - \phi}{\tau},$$

where T is the inside temperature and ϕ is the ambient temperature opposite the thermostat. The loss of heat per unit area as a function of x, the distance along the axis of the cylinder, is

$$b = \frac{\Delta\phi}{\tau h} x + c' - \frac{\Delta\phi}{2\tau}.$$

The net production of heat per unit area is then $c'-b$, which is simply $(-\Delta\phi/\tau)(x/h-\frac{1}{2})$. Because the wall of the cylinder is thin compared to its radius and length, it is possible to approximate the rate of heat production per unit volume as $(-\Delta\phi/\tau d)\ (x/h-\frac{1}{2})$ and application of the continuity equation equates this expression to $-\mu\nabla^2 T$. For this one-dimensional case of heat flow parallel to the wall,

$$\frac{d^2T}{dx^2} = \frac{\Delta\phi}{\mu\tau d}\left(\frac{x}{h} - \tfrac{1}{2}\right)$$

$$\frac{dT}{dx} = \frac{\Delta\phi}{\mu\tau d}\left(\frac{x^2}{2h} - \frac{x}{2}\right) + N,$$

where N is the constant of integration and is approximately equal to $-1/\mu$ times the longitudinal flow of heat per unit area from the end plate of the cylinder ($x=0$). To a first approximation the end plate is at uniform temperature ($r \ll h$) and the flow of heat from it to the cylinder wall can be taken as $\pi r^2(c'-b_{x=0}) = (\Delta\phi/2\tau)\pi r^2$ which corre-

sponds to a flow per unit area into the end of the cylinder of $\Delta\phi r/4\tau d$. Substituting for N we have,

$$\frac{dT}{dx} = \frac{\Delta\phi}{\mu\tau d}\left(\frac{x^2}{2h} - \frac{x}{2} - \frac{r}{4}\right),$$

and

$$\Delta T = \frac{-\Delta\phi}{\mu\tau d}\left(\frac{h^2}{12} + \frac{rh}{4}\right),$$

where now, ΔT is the difference in temperature between the ends of the cylinder caused by a corresponding difference in ambient temperature of $\Delta\phi$.

Although the use of alternating layers of high and low conductive material is a logical way to obtain good temperature distribution, it leads to expensive construction and excessive weight. To economize on the weight of metal oven walls the writer has resorted to the use of several thermostats spaced symmetrically around a single oven. Each thermostat controls the production of heat in its own immediate neighborhood and even though each thermostat may operate at a slightly different temperature the resulting temperature distribution within the oven remains more nearly constant than is possible with a single thermostat.

The best that can be expected of any thermostat is that it hold its own temperature constant and if other points are held constant it is only because they are in good thermal contact with the thermostat. With plural points of control there are no regions of the oven remotely located relative to a controlled point.

Plural points of control seem to be superior even to the use of a thermostat, such as a resistance bridge, that can be spread uniformly over the oven wall. Although the resistance bridge averages the temperature of the oven and regulates the heat supply accordingly, it is obviously possible for the temperature distribution within the oven to change without changing the average temperature.

ESSENTIAL COMPONENTS OF GRAVIMETER OVEN

The features so far presented serve as a practical guide in the design of a thermal oven for a gravimeter.

Since very close control of the temperature is necessary it is very probable that self sustained oscillations will exist. Highest sensitivities are obtained when the smallest temperature change which a given thermostat can detect, is used to switch the heat source entirely on or

off; i.e., use of the highest possible values of s in continuous control degenerates into relay-type thermostats. It is therefore desirable to provide an attenuating layer (a layer of material for which $\rho c/k$ is large) between the thermostat and the inside of the oven. See Fig. 4.

To insure a uniform temperature within the oven a distributing layer should surround the attenuating layer. For highest efficiency this distributing layer should be made of aluminum containing a plu-

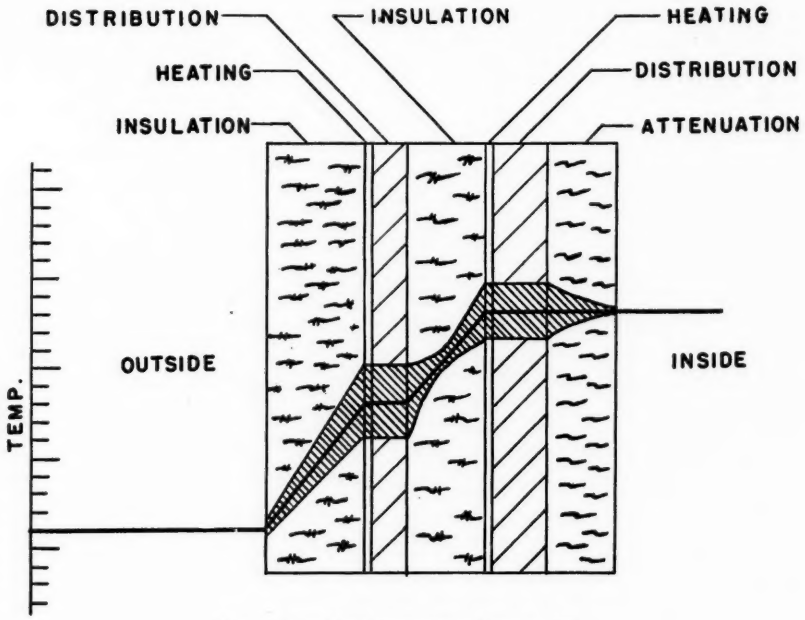

FIG. 4. Doubly thermostated oven wall.

rality of thermostats, or it should be divided into two or more layers separated by insulating material. To economize on total heat consumption the heating coils and thermostat should be located on the innermost distributing layer. The thermostat should be in as good thermal contact as possible with both the heat source and distributing layer in order that x_0 be small. The resulting high frequency for the thermostat cycle materially improves the efficiency of the attenuation layer.

Mercury-in-glass thermostats have been found very satisfactory for use with gravimeter ovens because of their stability and the simplicity of the auxiliary control equipment which they require. When their sensitivity is so high that the backlash is of the order of

.02°C. they are sensitive to vibration; i.e., road shocks cause "chattering" of the mercury column against the contact electrode. The chattering is caused by the fact that the thin glass bulb containing the heavy mercury deforms when accelerated. This deformation can be greatly reduced by inserting the mercury bulb in a steel tube filled with mercury. The mercury bath cancels the inertia of the mercury in the bulb and also provides a good thermal connection between the bulb and its environment. Introduction of time delay in the control circuit is undesirable because it increases the over- and undershooting in the thermostat.

If the glass bulb of the thermostat is too thin the mean operating temperature will vary slightly with barometric pressure; a negligible effect except in areas of large variations in altitude.

An insulation layer surrounds the distributing layer. The insulation should of course have a low value of k to economize on the heat supply as well as to increase the value of μ and improve the efficiency of shielding against temperature gradients. However, in addition to a low k, it is important that the insulation have as large a value of $\rho c/k$ as possible in order to attenuate short-time fluctations in ambient temperature. Thus wool felt is preferable to kapok even though both have the same conductivity.

To reduce long-time fluctuations in the ambient temperature it is convenient to surround the insulating layer with a second thermostated distributing layer. This second distributing layer is held at an approximately constant temperature several degrees lower than the inside temperature. Reference to Eq. 18 shows how the resulting constancy of $(T-\phi)$ and corresponding smallness of $d\phi$ will aid greatly in the reduction of dT to a very small value. Voltage regulation is also desirable to reduce dV/V to a low value. This second heating and distributing layer acting with its inner companion also gives the oven the advantage of multiple shielding against temperature gradients.

Finally, a second layer of insulation is added and it should have the same properties as the first insulating layer. On first consideration one may be inclined to make this second insulating layer quite thick in order to economize on the amount of heat necessary to maintain the outer heating layer at its proper temperature. However, the temperature difference between the inner and outer heating layers requires that a certain amount of heat, q', flow from the former to the latter and then continue outward through the second insulating layer. The

heat q' flowing through a thick outer layer of insulation would produce a large temperature drop and it would be necessary to limit the rise in ambient temperature to a value rather low relative to the inside temperature.

Even in the case of a single heating layer it is not desirable to use too much insulation because, as the ambient temperature approaches the inside temperature, the heating cycle becomes so unsymmetrical as well as of such low frequency that the attenuating layer is no longer effective. If the inside temperature is raised so as to be well above the highest ambient temperature the corresponding increase in heat supply that is then required, cancels the economy of thick insulation.

A cross-section of what might be considered an ideal oven wall for a gravimeter is shown in Fig. 4. The heavy line is a graph of the mean temperature through the wall and the shaded area the temperature variation.

The writer wishes to thank Mr. H. C. Cortes and Dr. J. P. Minton of the Magnolia Petroleum Company for their kind permission to present this discussion.

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THE ANALYTIC BASIS OF GRAVITY INTERPRETATION*

D. S. HUGHES†

ABSTRACT

One method of gravity interpretation involves the use of analytic continuation processes. In this discussion the resolving power of this method is tested numerically.

Using hypothetical structures comprising single and double blocks, a surface-gravity profile is derived. Using these values as an "observed gravity" profile, the "continuation" method is applied to compute the gravity at intermediate depths. Comparing these computed values with the actual (directly computed) gravity profile at these depth-planes, the resolving power of the continuation method is demonstrated. It is shown that a very high precision in the observed data is necessary for very accurate resolution of structures.

The problem of deriving the underlying structure from observations of the gravitational attraction at the surface has received considerable attention. A large number of graphical and mechanical schemes of computation have been evolved for calculating the gravitational attraction of a given mass distribution, but the more difficult inverse problem of computing the mass distribution from the observations has received no satisfactory treatment. This latter problem is in fact known to have, in general, no unique solution. One common method of obtaining a solution is to compute the gravitational attraction of various simple mass configurations and then compare these computed values with the observed values. By varying the depth and size of the assumed configurations it will usually be possible to reproduce the observations with any desired accuracy. While this process is of great practical utility it must be clearly recognized that it does not give a unique solution and the actual structure that gives rise to the observations may bear little or no resemblance to the structure derived by this method.

Several writers have called attention to the fact that the solutions are more determinate for shallow than deep structure. Shallow and deep in this connection are terms relative to the size of the structure. In order to gain a practical advantage from this fact various attempts have been made to find a method of computing the gravitational attraction at any given depth below the surface from observations made at the surface. Thus the object of this method is to take the surface gravity map and translate it into the map that would be obtained

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† Shell Oil Co., Houston, Texas.

were it possible to make the observations at some fixed depth below the surface. Obviously this depth may be chosen so that the map is obtained on a plane as near the structure as desired. Within certain limitations this problem may be solved and thus, theoretically, from a surface gravity map we should be able, by constructing maps on successively deeper planes, to attain any desired degree of resolution. Actually this method suffers from the same limitations as the method of assuming simple mass distributions and then varying them in such a way as to fit the observations. In fact a modification of this latter process can be shown to give a rigorous solution of the problem of computing gravity at depth from the observed values at the surface.

In computing the anomalies from the observations, corrections are usually made for the shape of the earth, elevation, topography, isostasy, etc., and thus the principal features of the earth are accounted for and the computed anomaly is effectively the attraction of anomalous density distributions located in an outer shell of the earth 100 kilometers or less in thickness. This shell is spheroidal but as its thickness is small compared with its radius a restricted neighborhood may be considered plane. Its upper surface (actual surface of the earth) will be taken as the (x, y)-plane and the z-axis will be taken positive upward.

Then $g(x, y, z)$ is the attraction of anomalous masses located below the plane $z=0$ at every point (x, y, z). In particular $g(x, y, 0)$ is the observed anomaly at the point (x, y). H. M. Evjen[1] has shown that from $g(x, y, 0)$ it is possible by a simple integration to compute $g(x, y, z)$ for z greater than zero and furthermore that the successive derivatives of g with respect to z may be computed at all points for which $z=0$. With these derivatives it is then possible to compute $g(x, y, z)$ for values of $z<0$ by means of Taylor's expansion. This is essentially the standard process of analytic continuations.

If we denote by $g(x, y, -h)$ the gravitation attraction on a plane h below the surface, the attraction at the surface is

$$g(x, y, 0) = 1/(2\pi) \int_{-\alpha}^{+\alpha} \int_{-\alpha}^{+\alpha} \frac{g(u, v, -h)h \, du \, dv}{[(x-u)^2 + (y-v)^2 + h^2]^{3/2}} \cdot \quad (1)$$

Since $g(x, y, 0)$ is known and $g(u, v, -h)$ unknown this expression is an integral equation for the unknown $g(u, v, -h)$. In the following we shall be concerned only with one set of values of (x, y) and hence this set

[1] H. M. Evjen: "Place of Vertical Gradient" GEOPHYSICS, January, 1936.

may without loss of generality be taken to be (o, o) and only the z coordinate will be specified explicitly.

Polar coordinates r, θ, are more convenient than the rectangular coordinates u, v. With these alterations Eq. (1) becomes,

$$g(o) = 1/(2\pi) \int_0^{\alpha} \int_0^{2\pi} \frac{g(r, \theta, -h) h \, r dr \, d\theta}{(r^2 + h^2)^{3/2}}. \tag{2}$$

In Eq. (2) the variable θ is involved only in $g(r, \theta, -h)$. Hence, setting

$$\bar{g}(r, -h) = 1/(2\pi) \int_0^{2\pi} g(r, \theta, -h) d\theta,$$

Eq. (2) may be written

$$g(o) = \int_0^{\alpha} \frac{\bar{g}(r, -h) h \, r dr}{(r^2 + h^2)^{3/2}}. \tag{3}$$

This equation may be solved by the method of iteration or repeated approximation. As a first approximation we may assume that $\bar{g}(r, -h)$ in the integral is identical with $\bar{g}(r, o)$ and then compute an approximate value of gravity at the surface.

Denoting the degree of approximation by subscripts,

$$g_0(-h) = g(o)$$

$$g_0(o) = \int_0^{\alpha} \frac{\bar{g}(r, o) h \, r dr}{(r^2 + h^2)^{3/2}}. \tag{4}$$

The computed gravity $g_0(o)$ at the surface is in error by

$$g(o) - g_0(o) = \int_0^{\alpha} \frac{[\bar{g}(r - h) - \bar{g}(r, o)] h \, r dr}{(r^2 + h^2)^{3/2}}. \tag{5}$$

This error may be regarded as a new anomaly to be accounted for and as before we may assume that a better approximation will be given by

$$g(o) - g_0(o) = g_1(-h) - g(o),$$

or solving,

$$g_1(-h) = 2g(o) - g_0(o). \tag{6}$$

But it is obvious by reference to Eq. (4) that

$$g_0(o) = g(h),$$

or that $g_0(o)$ is the anomaly that would have been observed on a plane h above the surface and

$$g_1(-h) = 2g(o) - g(h). \tag{7}$$

The substitution of this improved approximation for $\bar{g}(r, -h)$ in Eq. (3) will give a better approximation for the surface gravity.

$$g_1(o) = \int_0^\alpha \frac{\bar{g}_1(r, -h)h\, r dr}{(r^2 + h^2)^{3/2}}. \tag{8}$$

Substituting $g_1(-h)$ from Eq. (7) this equation may be written

$$g_1(o) = 2g(h) - g(2h), \tag{9}$$

and the error of this approximation is

$$\begin{aligned} g(o) - g_1(o) &= g(o) - 2g(h) + g(2h) \\ &= \int_0^\alpha \frac{[\bar{g}(r-h) - \bar{g}_1(r-h)]h\, r dr}{(r^2 + h^2)^{3/2}}; \end{aligned} \tag{10}$$

and again we may assume the approximate value of the error to be

$$g(o) - g_1(o) = g_2(-h) - g_1(-h);$$

or substituting from equations (7) and (9)

$$g_2(-h) = 3g(o) - 3g(h) + g(2h). \tag{11}$$

This approximation may in turn be substituted in Eq. (3) and $g_2(o)$ computed.

$$g_2(o) = 3g(h) - 3g(2h) + g(3h). \tag{12}$$

By continually separating this process it is found that the nth approximation to $g(-h)$ is

$$g_n(-h) = \sum_{k=0}^{n} (-1)^k \binom{n+1}{k+1} g(kh), \tag{13}$$

and the nth approximation to the observed anomalies is

$$g_n(o) = \sum_{k=0}^{n} (-1)^k \binom{n+1}{k+1} g((k-1)h.) \tag{14}$$

Thus far it is not known whether or not this process is convergent, that is whether or not the successive approximations are really better approximations. In the form given above it is not possible to answer

this question. The convergence of the process depends upon the g's and cannot be investigated until they are specified. Eq. (14), it will be noted, is obtained from (13) merely by adding h to the argument of all g's. Hence it is sufficient to investigate only Eq. (13).

From Eq. (3) it is obvious that

$$g(kh) = \int_0^\alpha \frac{\bar{g}(r, o)\, kh\, r dr}{(r^2 + k^2h^2)^{3/2}}. \tag{15}$$

By a well known relation[2]

$$\frac{kh}{(r^2 + k^2h^2)^{3/2}} = \int_0^\alpha e^{-kh\lambda} J_0(\lambda r)\lambda d\lambda. \tag{16}$$

So that we may write

$$g(kh) = \int_0^\alpha \bar{g}(r, o) r dr \int_0^\alpha e^{-kh\lambda} J_0(\lambda r)\lambda d\lambda,$$

or

$$g(kh) = \int_0^\alpha e^{-kh\lambda}\lambda d\lambda \int_0^\alpha \bar{g}(r, o) J_0(\lambda r) r dr. \tag{17}$$

The first form is not convergent for $k = o$, although obviously it is for all positive values of k. The second form is convergent for $h = o$, and is merely the Fourier-Bessel integral. Substituting Eq. (17) for the g's in Eq. (13) there is obtained,

$$g_n(-h) = \int_0^\alpha \sum_{k=0}^{n} (-1)^k \binom{n+1}{k+1} e^{-kh\lambda}\lambda d\lambda \cdot \int_0^\alpha \bar{g}(r, o) J_0(\lambda r) r dr; \tag{18}$$

but

$$\sum_{k=0}^{n} (-1)^k \binom{n+1}{k+1} e^{-kh\lambda} = e^{h\lambda}[1 - (1 - e^{-h})^n],$$

and

$$g_n(-h) = \int_0^\alpha e^{h\lambda}[1 - (1 - e^{-h})^n]\lambda d\lambda \int_0^\alpha \bar{g}(r, o) J_0(\lambda r) r dr. \tag{19}$$

[2] A. G. Webster: "Partial Differential Equations of Mathematical Physics." Stechert & Co., 1927, page 406.

In this equation if n becomes large without limit

$$g(-h) = \int_0^\alpha e^{h\lambda}\lambda d\lambda \int_0^\alpha \bar{g}(r, 0)J_0(\lambda r)rdr. \qquad (20a)$$

If $g(x, y, 0)$ is constant in the y direction or the observed values are not a function of y, Eq. (13) still applies; however, Eq. (202) becomes,

$$g(-h) = 1/\pi \int_0^\alpha e^{h\lambda}d\lambda \int_{-\alpha}^{+\alpha} g(x, 0) \cos \lambda x \, dx. \qquad (20b)$$

The equations are rigorous formulae for computing the attraction on a plane at depth h from observations at the surface. The integrals will be convergent only if h is less than the depth to the shallowest singularity of $g(r, 0)$. Eqs. (20) are of little or no practical utility in the actual solution of the interpretation problem.

If $g(r, 0)$ were given in analytical form it would offer a solution of the problem but the observations are point to point numerical values and the numerical solutions of Eqs. (20) are hopeless. These equations do, however, offer confirmation of the limiting process and of the finite forms given by Eqs. (13) and (14). These latter equations must operate under the same limitations as Eqs. (20), i.e., h must be less than the depth of the shallowest singularity of $g(r, 0)$. A priori, this depth is not known; however, if for some selected h the successive approximations from Eq. (13) do not approach a limit, or if the integrals in Eqs. (20) do not converge, the selected h is too large and a smaller value must be chosen.

In contrast to Eqs. (20), numerical computations may be carried out with Eq. (13). It is only necessary to compute $g(kh)$ for a selected number of planes above the surface. Thus at any point $g_n(-h)$ may be computed from Eq. (13). This process, while long, is not impossible. Eq. (13) is, however, the condition that the $(n+1)$th difference of a function given at the $(n+2)$ points $-h, 0, h, 2h, \ldots nh$, shall be zero; in other words, that the $(n+2)$ values can be fitted by a polynomial of the nth degree. It is thus simply the polynomial extrapolation formula.

It is well known that large errors are inherent in such an extrapolation and are unavoidable. These errors are not introduced specifically by the above mathematical derivation, but are inherent in any scheme of interpretation.

The mathematical derivation of Eqs. (13) and (20) is merely an

analytic formulation of the method of interpretation by assuming a primary distribution and then introducing corrections so that the final structure will reproduce the observations. It may be urged that in the present case the first approximation was very crude and that a better first approximation would give a better convergence. This, however, is not true. A good first approximation makes fewer steps necessary to achieve a selected accuracy but does not increase the accuracy of the final result. This is easily seen to be true since if the process converges at all some one of the successive $g_n(-h)$ will approach as closely as we please to the true value of $g(-h)$. This particular $g_n(-h)$ may be regarded as the first solution and the process continued from there, the final accuracy will not be changed.

A very useful result which may be derived from these equations is the effect of errors in observations. Error in this connection denotes any deviation of the observed value from the true attraction of the subsurface structure. Thus not only instrumental errors are included but also errors due to improper or incorrect reduction formulae and errors due to assumptions of incorrect densities for the strata above sea level. Ordinarily the topographic correction is not computed and this introduces an additional error.

If Eq. (13) is used to compute the anomaly $g_n(-h)$ below the surface $g(0)$, the observed value directly above this point is multiplied by n, the degree of approximation, and any error in $g(0)$ is thus increased n times. The $g(h)$ of Eq. (13) is multiplied by $n(n-1)/2$ and consequently its error is increased even more; on the other hand, $g(h)$ is computed by an integration over all the surface observations and thus random errors will, to a large extent, be cancelled. The degree of cancellation cannot be formulated exactly but it is apparent that if the station spacing is small compared with h, the cancellation of random errors will be much more effective than for spacings of the same magnitude as h. If the error in all the $g(kh)$ was the same as that in $g(0)$, the probable error of $g_n(-h)$ would be the probable error of $g(0)$ multiplied by the square root of the sum of the squares of binomial coefficients in Eq. (13); on the other hand, if the errors of $g(kh)$ were zero, the error in $g_n(-h)$ would be n times the error of $g(0)$. Thus for a fifth order approximation, the error will be multiplied by some factor greater than 5 and less than 16.

Hence the degree of approximation that can be used is determined by the accuracy of the data and the allowable error in final results. Eqs. (20a) and (20b) correspond to an infinite degree of approximation

and hence can only be applied to data of infinite accuracy, or in other words, to data given by an analytic formula.

As an example of the application of these equations the two structures shown in Fig. 1 have been chosen. The computed gravity profiles for each structure for several different depths are shown. A density difference of 0.3 has been assumed in computing the profiles. For the structures actually drawn a constant should be added to the curves for the broader structure since its base level is different. However, in the

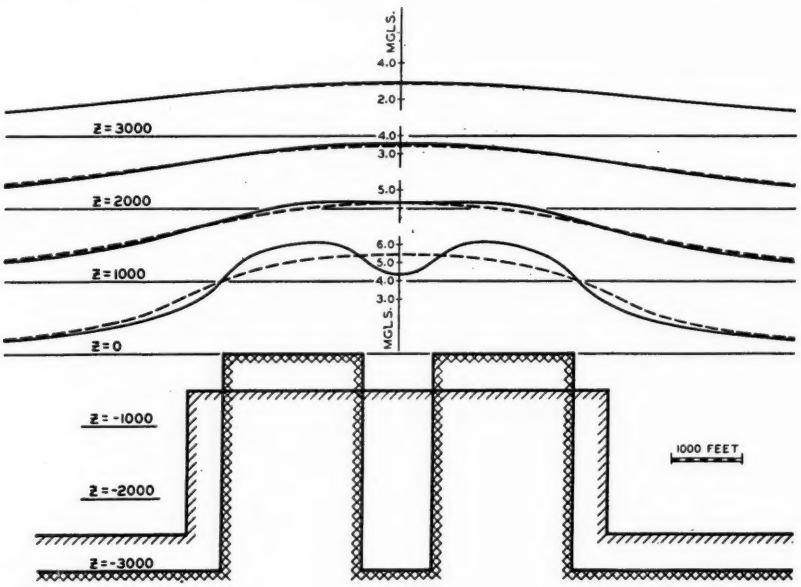

FIG. 1. Computed gravity profiles for two hypothetical structures at several assumed depths, Z. Dashed lines are for single block structure; solid lines are for double-block structure.

reduction of field observations we never obtain an absolute anomaly but only a relative one. In other words, the actual numerical anomaly has no meaning. The interpretation is based on the excess or deficiency of the anomaly at one point as compared with another. These two structures shown here have been chosen in such a way as to be different as possible and yet to give as similar anomalies as possible. It will be noted that if the double structure reaches the surface and the single structure is 500 feet deep the two g curves are quite different. However, if both structures are placed 1000 feet deeper the g errors are

very similar showing a maximum difference of only 0.3 milligals. At a depth of 2000 feet the difference in the g curves is only 0.15 milligals. and at 3000 feet it is less than 0.10 milligals.

In order to demonstrate the use of the equations derived earlier,

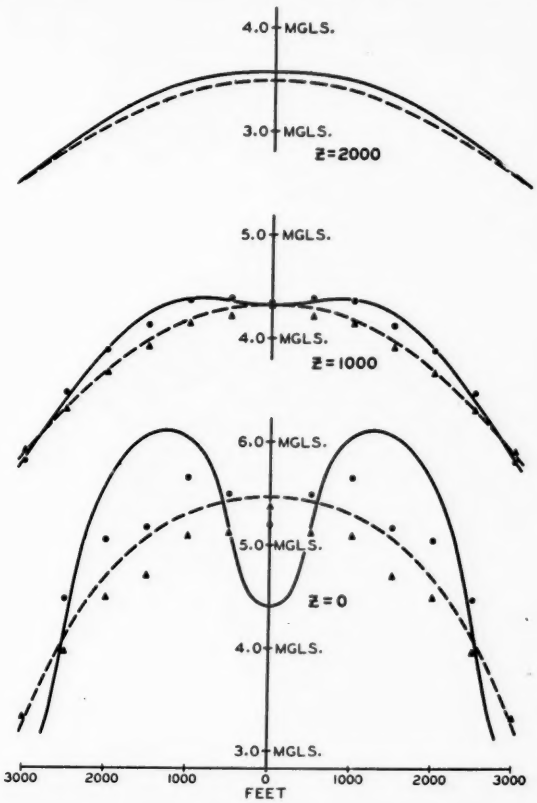

FIG. 2. Showing the resolution obtainable by "continuation methods" applied to gravity profiles. Circular and triangular points respectively, show "continuation" of observed gravity ($Z=2000$) for double and single block structure of Fig. 1 at $Z=1000$ and $Z=0$ planes. Compare points with actual gravity in these planes as shown by the curves.

the computed g curves at 2000 feet above the structure have been selected. These curves and also the curves for 1000 feet and zero are shown in Fig. 2 plotted to a larger vertical scale. The upper curves ($z=2000$ feet) have been used as the observed curves and by means of Eqs. (13) and (15) the observations at 1000 feet and 0 have been com-

puted. These points are shown by circles for the double structure and triangles for the single structure.

Fairly satisfactory reproductions of the curves at 1000 feet are obtained and the resolution is increased somewhat. The computed points at $z=0$ show a resolution but so far off the actual curves that it is evident that the corresponding structures would be quite different from the original structures.

A fifth degree approximation was used in computing these points. A more accurate reproduction cannot be obtained by taking a higher order formula. The computation of the original curves is accurate to 0.01 mgl. To increase the accuracy of the project points it would be necessary to use not only a higher order approximation but also a more accurate original curve. The departure of the projected points from the curves should not be regarded as an error. These points represent curves at depth that will reproduce the original curves within the limits of accuracy of the observations. In other words, these projected points represent possible interpretations of the observations within the accuracy of the observations.

THE CROSBYTON ANOMALY, SOUTHEASTERN CROSBY COUNTY, TEXAS*

ETHEL WARD McLEMORE,† PAUL WEAVER,‡ AND DONALD C. BARTON§

FOREWORD

The purpose of this study has been the interpretation of the most probable structure producing the slightly subcircular anomaly at Crosbyton, as mapped by the pendulum, torsion balance, magnetometer, and dip needle. Work was begun in 1935 under the direction of Dr. Barton, who was to have written the geological considerations. All calculations were completed in 1938, but unfortunately the geological interpretation was not written by Dr. Barton before his death, July 8, 1939. At my request, since he had discussed the Crosbyton anomaly with Dr. Barton many times, and was quite familiar with the work we were doing, Mr. Weaver kindly consented to write the geological interpretation and help me with the completion of the paper. It is due to his knowledge and able assistance that the paper has been brought up to date in the light of subsequent drilling by the Gulf Oil Corporation.

HISTORY AND LOCATION

The Crosbyton high lies nearly in the center of the high plains of West Texas, approximately 45 miles southeast of Lubbock, and near the common corner of Crosby, Dickens, Kent, and Garza Counties. The high is named for the County seat, Crosbyton, of Crosby County, which is about fifteen miles north from the apex of the geophysical picture.

The average elevation of the area is approximately 2300 feet, with low relief. Drainage is to the southeast through the White River, one of the tributaries of the Brazos. There are no particular difficulties in transportation, nor in surface conditions which obstruct geophysical operations.

Although until recently there has been no important oil or gas development near the Crosbyton high, it marked a milestone in the economic geology of Texas, because it was from a well drilled at Spur,

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§ Died July 8, 1939, Houston, Texas.

in Dickens County, on the northeast side of the feature, that the first potash salts were reported from the Permian. Dr. J. A. Udden reported on this occurrence,[1] and it led to the drilling of a number of special test wells, subsequent to the World War which demonstrated the importance of a domestic source of potash in this country. This campaign of test wells was instrumental in the development of the present operating potash mines in New Mexico.

The Spur well was a local effort, drilled under pioneer conditions (Swenson fee #1, NW/4, Sec. 225, H. & G. N. RR., Dickens County), and fifty-two months elapsed from spudding until the total depth of 4489 feet was reached in November, 1913. It was at that time the deepest well that had been drilled in Texas.

In January, 1926, drilling was begun on a well in Garza County by the Deep Rock Company, about four and three-fourths miles south and two and one-fourth miles west from the northeast corner of Garza County. It was not until October 23, of that same year that the total depth of 3502 feet was reached (Deep Rock, Swenson #1, Center Sec. 36, Blk. 2).

In 1923 the first large production in West Texas was brought in at Big Lake, about 100 miles south of Crosbyton, causing immediate attention by geologists. This was almost simultaneous with the introduction of geophysical instruments in the Gulf Coast; but, since these were presumed to be useful primarily for the discovery of salt domes, they were not taken to West Texas immediately. However, since granite was known to be present in West Texas in the Panhandle, and since large areas seemed to be difficult to work as to surface geology, it was natural that attention should be given to an attempt to find some relation of buried granite features to structure in areas where surface geology was inconclusive. Thus the dip needle was tried in 1925, in the Panhandle. In 1926 the Askania magnetometer came into use in a general reconnaissance of the entire Permian Basin by several companies. It was on the basis of detailed work with this instrument that the Gulf Production Company drilled the #1A Swenson. There also at this time the refraction seismograph and the torsion balance were introduced.

The first mention in the literature of the Crosbyton high was in February, 1928, at the meeting of the American Institute of Mining and Metallurgical Engineers in New York City, where Dr. Barton

[1] J. A. Udden, Deep Boring at Spur, University of Texas Bulletin, 363, October 5, 1914.

presented a paper.[2] In the discussion Mr. DeGolyer[3] asked about the Crosbyton high; and the following comments by the senior author are inserted her, since the original publication is not commonly available.[3]

It seems to me it must be a big batholith. Mathematically, it could be accounted for by a large structural high of limestone, rising to within 2500 feet of the surface and sloping off rather gently to a depth of three miles, at a distance of about twenty miles from the crest. . . . We can get a series of pictures of possible structures that are all equally probable mathematically. In general they may have a minimum depth or a maximum depth. In this case we could not bring the structure within 2500 feet of the surface by any reasonable assumption, but the top of it might be 5000 feet just as easily. The Gulf Production Company has drilled a test below 5000 feet without finding anything but the normal stratigraphic section.

The well by the Gulf Production Company to which the senior author referred was located in the northeast corner of Garza County (NW corner, Sec. 67, H. & G. N. RR., Blk. 2) and was the Swenson #1A, completed March 24, 1928, at 5105 feet. On zonal correlation this well was correlated as thirty-six feet lower than that of Deep Rock.

Subsequently, in 1938, another well (#1B Swenson) has been drilled by the Gulf Oil Corporation, which found granite at 8085 feet, continuing in that formation to the total depth of 8104 feet; and followed by a second well (#1C Swenson) to a depth of about 8414. All the calculations in this article were completed prior to the drilling of these wells. In the geologic interpretation which concludes this paper will be found comments on comparison of the calculations with the results of these wells, the only deep tests drilled in the general area since the geophysical work was done.

The following is an abstract of the projected paper written by Dr. Barton in 1937:

A large slightly subcircular anomaly has been mapped by pendulum, torsion balance, magnetometer, and dip needle, near Crosbyton in Northwest Central Texas. The width of the anomaly is approximately 40 miles, its gravitational amplitude 45 milligals and its magnetic amplitude 2500 gammas. A well which was drilled to a depth of 5105 feet, near the crest of the anomaly, is carried as normal by the subsurface geologists. According to mathematical calculations, the anomaly must be the effect of a flattened stock like mass whose vertical dimension is several miles. From geological considerations it must be the effect of a plutonic rock.

[2] D. C. Barton: "The E"tvös Torsion Balance Method of Mapping Geologic Structure," Geophysical Prospecting, 1929, A.I.M.E., pp. 416–466.

[3] *Op. cit.* p. 467.

GEOPHYSICAL INTERPRETATION

Data from independent surveys by four different instruments were used in an attempt to work out a composite profile across the anomaly, from which was calculated the probable structure producing this anomaly. These surveys were: pendulum determinations made by the

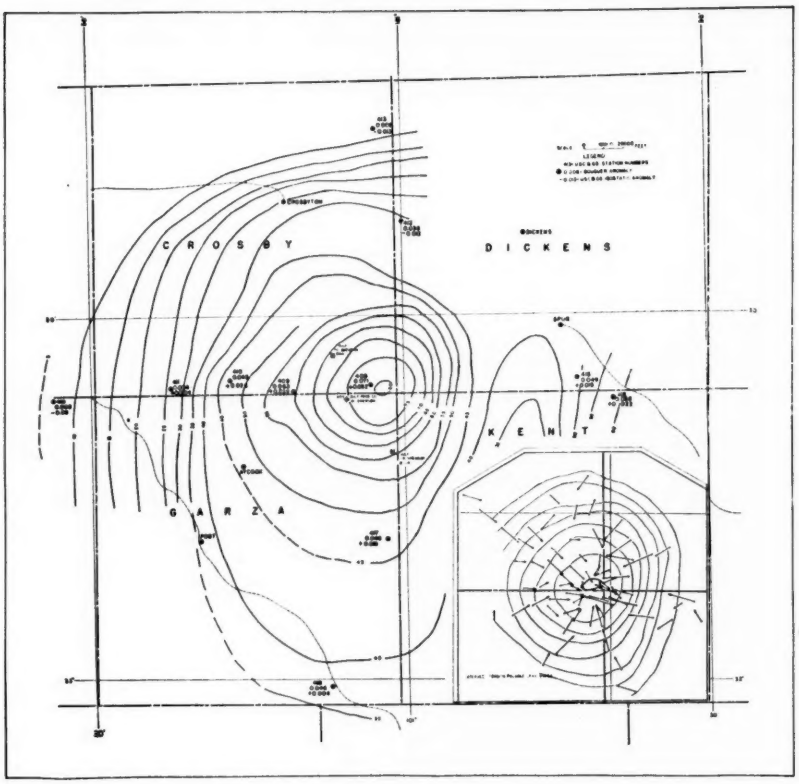


FIG. 1. Compromise isogams between torsion balance and Bouguer pendulum anomalies. Insert—Observed torsion balance gradients.

United States Coast & Geodetic Survey during the fall of 1933; torsion balance survey made by D. C. Barton for the Amerada Petroleum Corporation in May, 1927; magnetometer surveys made by Amerada with the Gepege Vertical Variometer early in 1927, and by the Texas Company with the Askania Vertical Field Balance about the same time; dip needle survey made by Amerada with the Hotchkiss Super Dip Needle in 1927.

Helmert's formula of 1901, $g = 978.030(1 + 0.005302 \sin^2\theta - 0.000007 \sin^2 2\theta)$ was used in the computation of theoretical values of gravity at the twelve stations, where gravity observations and latitude determinations were made by the United States Coast & Geodetic Survey. The observed values were adjusted to a common latitude of 33°30′ and sea-level; applying the elevation correction according to the

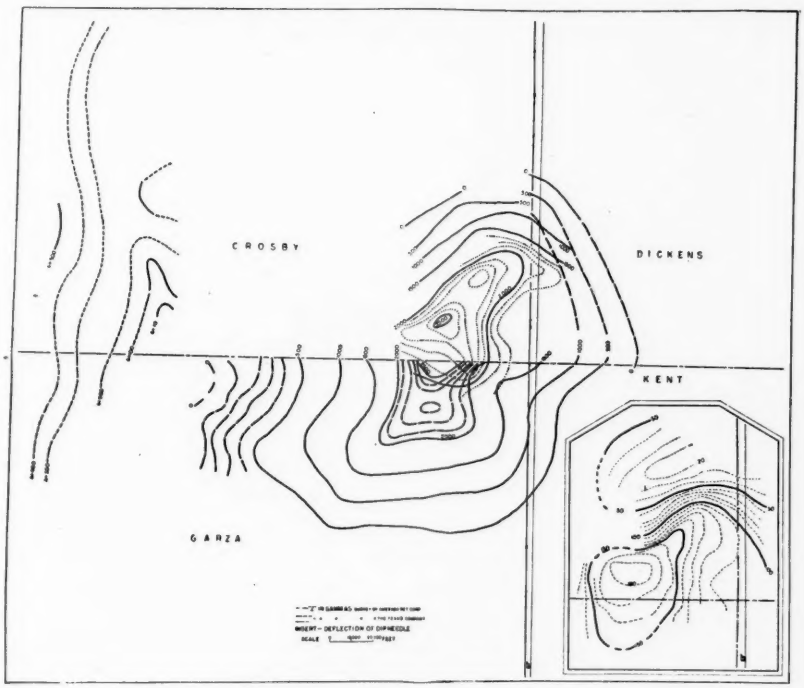


FIG. 2. Magnetic isogams. Insert—Deflection of dip needle.

Bouguer formula. From these calculated theoretical values of gravity and the adjusted observed values were derived the isostatic anomalies ($g_{obs.} - g_{theor.}$) which are shown on the map in Fig. 1.

Maps of the four surveys were plotted on a common scale of one inch equals to 10,000 feet (Figs. 1 & 2). From each of these a corresponding east-west profile was calculated. These are shown on Fig. 3. From these profiles a compromise profile was derived (Fig. 3a). Since the details of the slope of this profile are principally from torsion balance data, and its azimuth is nearly east-west, it is designated as the

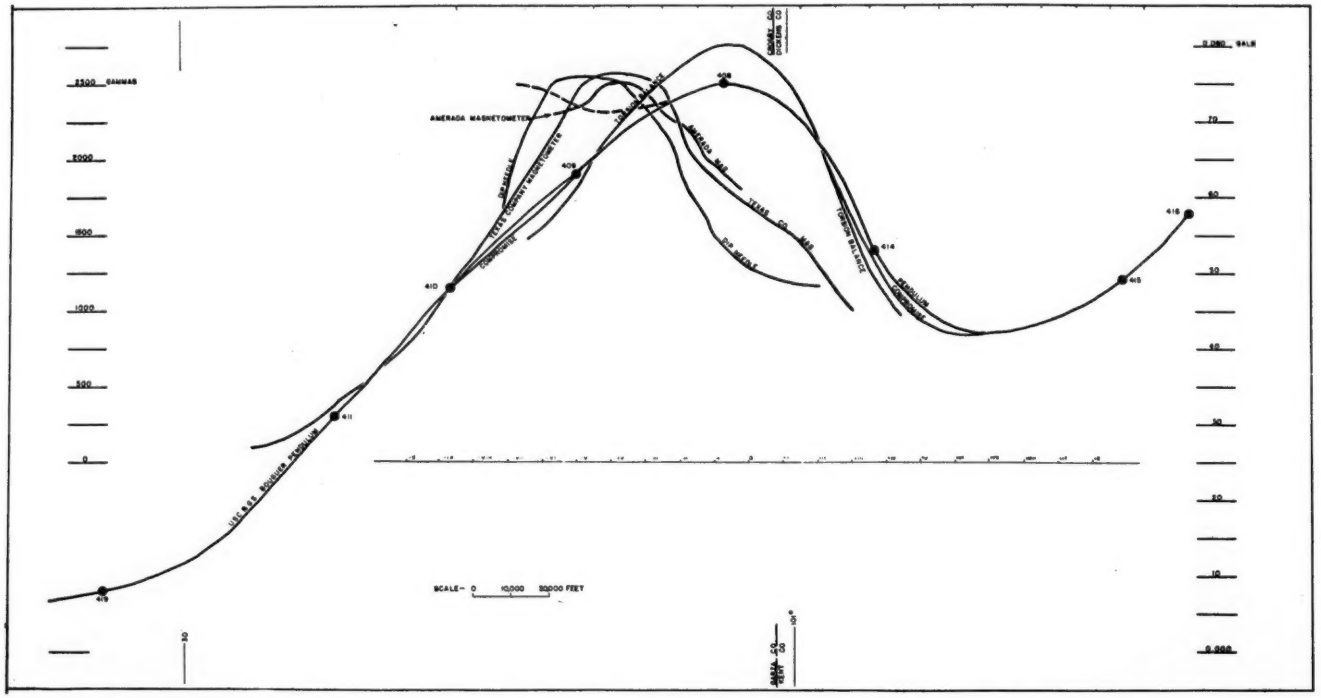


FIG. 3. Gravity profiles of four surveys.

"observed gradient profile" of the Crosbyton anomaly, or a U_{xz} profile in the language of the torsion balance.

The graphic method of calculation of gradient profiles from different assumed structures was carried through, employing a U_{xz} chart of 9:10:10 proportions,[4] for twenty stations selected at equal distances along the east-west cross-section (Figs. 3 and 3a show location of stations from which the values of the "observed gradient profile" could

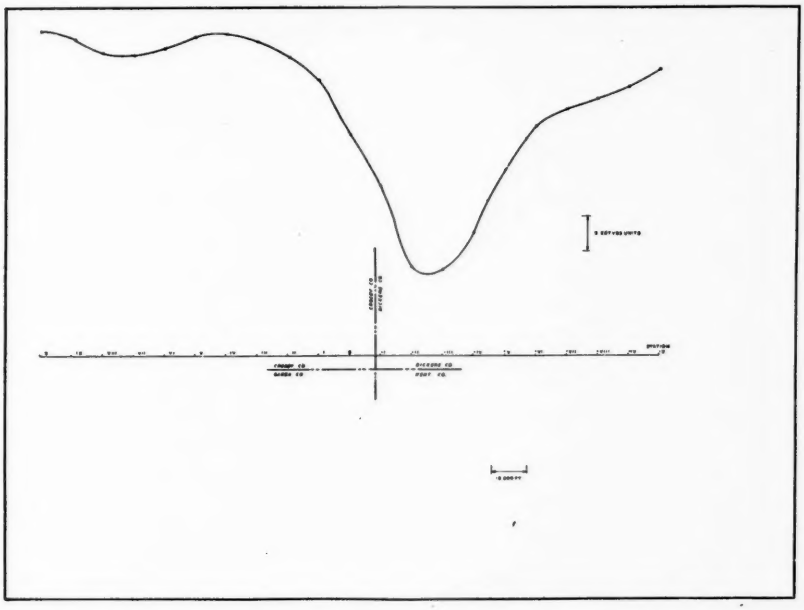


FIG. 3a. Observed gravity-gradient profile.

be read for comparisons with each assumed structure). In order to have the complete structure come within the dimensions of the chart, the scale of one inch equal to 2500 feet was used, the "observed gradient profile" being replotted on this scale. All results were subsequently replotted on the scale of one inch equal to 10,000 feet.

The U_{xz} chart was used for computation of three-dimensional figures because it is obvious from the geophysical contours that the Crosbyton high is due to some mass of nearly equal dimensions in any

[4] D. C. Barton: "Calculations in the Interpretation of Observations by the Eotvos Torsion Balance," Geophysical Prospecting, 1929. Amer. Inst. Min. Met. Eng., 1929, pp. 480–504.

horizontal direction. In the cross-sections comparing computed and observed gradients, only two dimensions are shown, except in Fig. 10 where the best fit between calculated and observed values indicated that the mass has the figure of a parallelopiped inclined to the horizontal as to its major dimension. In Fig. 10 the cross-section is shown in perspective.

The first assumed structure was a finite rectangular block ($A'B'C'D'$) with axis median with respect to the maximum and mini-

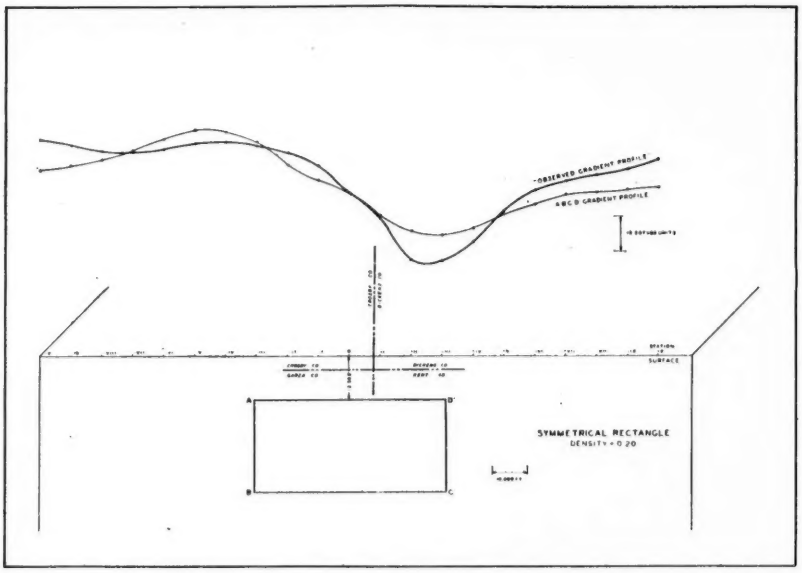


FIG. 4. Symmetrical rectangle—with profiles. The gravity profile is calculated for a three-dimensional mass with square horizontal cross-section.

mum of the anomaly. With variations of depth and position the gradient values at twenty stations were calculated, with constant size of the block. To obtain the average density contrast of the assumed structure, the average of the ratio of the observed to the calculated values at each station was taken; and, since the density enters in the chart as a multiplier, this average gives the density contrast. The least square method was used in selecting the most probable depth and position of this assumed structure. The two calculated gradient profiles of the two positions of the structure $A'B'C'D'$ which gave the least sums of the squares of the deviations were compared with the "observed gradient profile" (Figs. 4 & 5). A comparison of these two profiles with

the observed at each station shows that in the center of the cross-section there is a fair coincidence, with a much faster increase of the observed values eastward, and a slow tendency toward constancy of the two calculated profiles. Westward there is a consistency as far as Station −VII, when the observed values increase rapidly, while the calculated values seem to approach constancy, by slow decrease.

As this seemed to point to the possibility of a composite structure of a finite block of one density and a block of another density and same

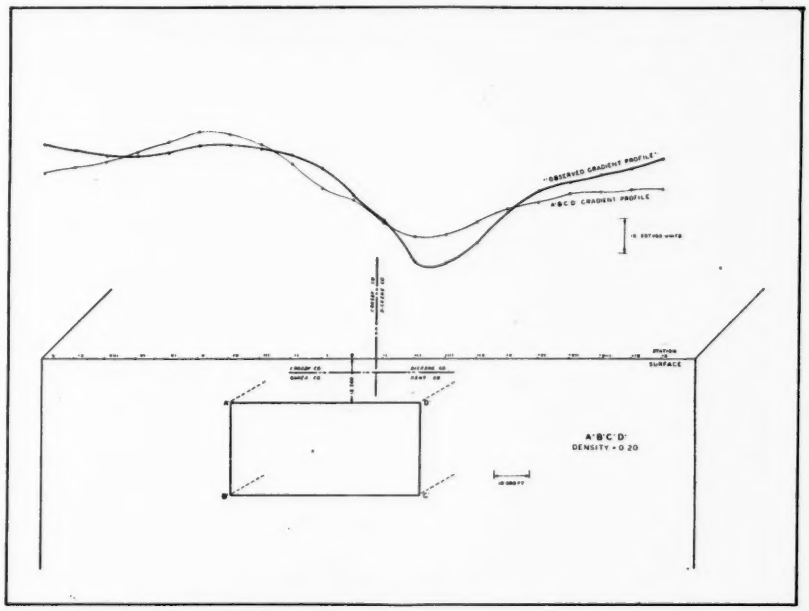


FIG. 5. Symmetrical rectangle; second position—with profiles. The gravity profile is calculated for a three-dimensional mass with square horizontal cross-section.

cross-section extending downward from the first to infinity, the values of the infinite block *MNOP*, with top at the base of the other block, were calculated. This composite structure and the gradient profile produced are shown in Fig. 6, with a comparison with the "observed gradient profile." While the inclusion of the infinite block gives a better fit eastward, positive values much higher than the observed throw it altogether out of comparison around Stations O to −VII inclusive, though giving the same increase of values past Station −VII as that of the observed.

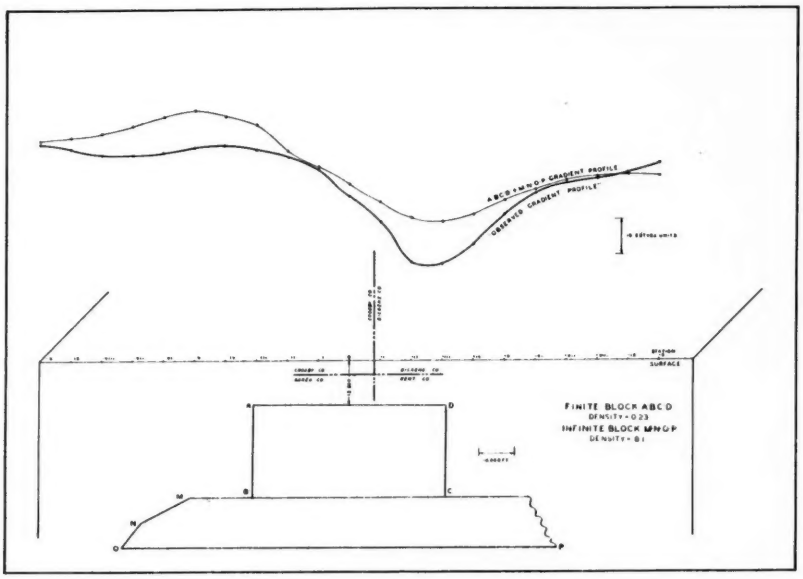
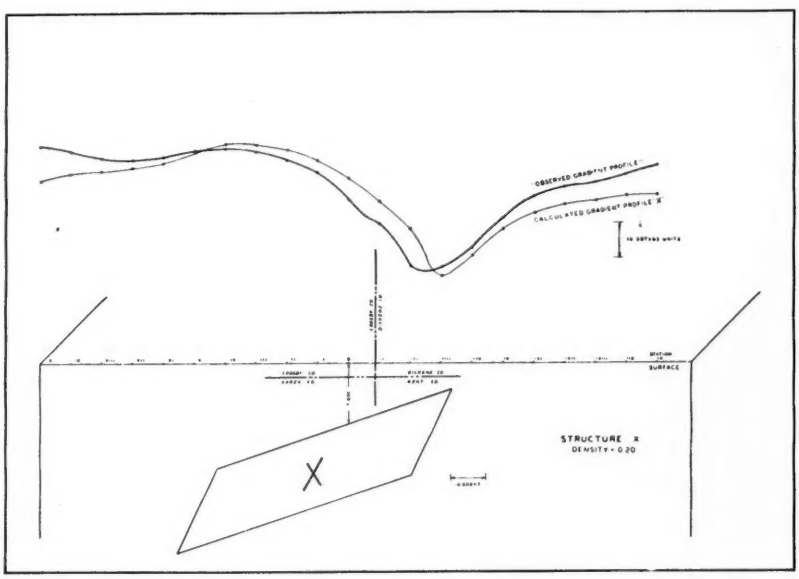


FIG. 6. Finite block with square horizontal cross-section together with block *MNOP*



FIGS. 7 & 8. Structure "*X*" with profiles.

In an attempt to get a better idea of the incongruency of the assumed structures, calculations for stations farther out from the observed gradient profile were located, both east and west. Calculations of the values of gravity at these stations proved that the tendency to decrease slowly westward, approaching zero as a limit, and increase slowly eastward continued with the outer stations.

Another structure "*X*" was assumed, a parallelopiped instead of a rectangle, dipping 20° westward, and deeper than the best position

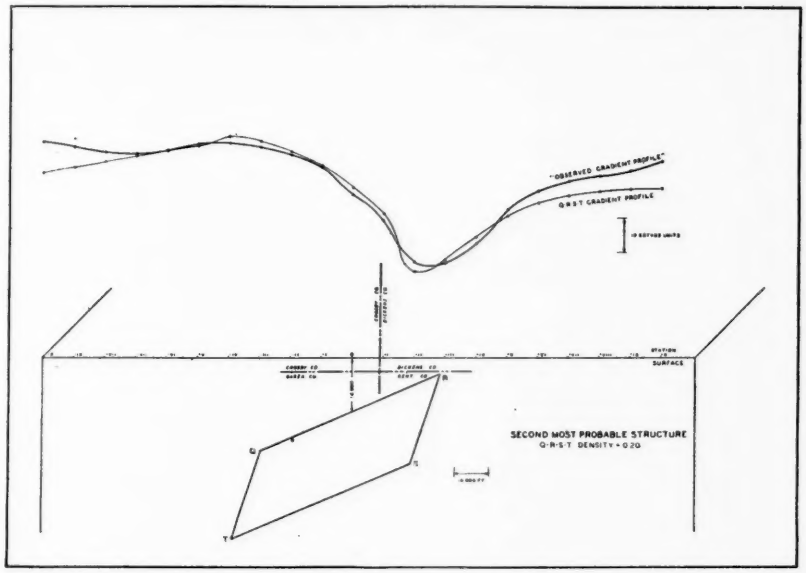


FIG. 9. Second most probable structure—with profiles. Block *QRST* has square horizontal cross-section.

calculated for the rectangle (Fig. 7). Comparison of the profile of this structure with the observed profile shows it a little too far eastward, and dipping at too large an angle (Fig. 8).

Two other parallelopiped structures were assumed: *QRST* dipping at an approximate angle of $22\frac{1}{2}°$ westward, and $W'X'Y'Z'$ dipping at an approximate angle of 15° westward, and moved over considerably westward of the center of the anomaly (Figs. 9 and 10). The sums of the squares of the deviations from the observed values of these calculations were the smallest yet obtained. Their profiles are shown compared to the observed in Figs. 9 and 10. Except for an unaccountable

discrepancy at Station +II, *QRST*, with a density contrast of 0.2, seemed to be the most probable structure. However, considering this discrepancy, *W'X'Y'Z'*, with an average density contrast of 0.23, gives a profile of nearest coincidence with the observed (Fig. 10).

Neither a composite profile of *W'X'Y'Z'* with the infinite block, nor variations of the size and shape of the infinite block seemed to give a better profile to the observed.

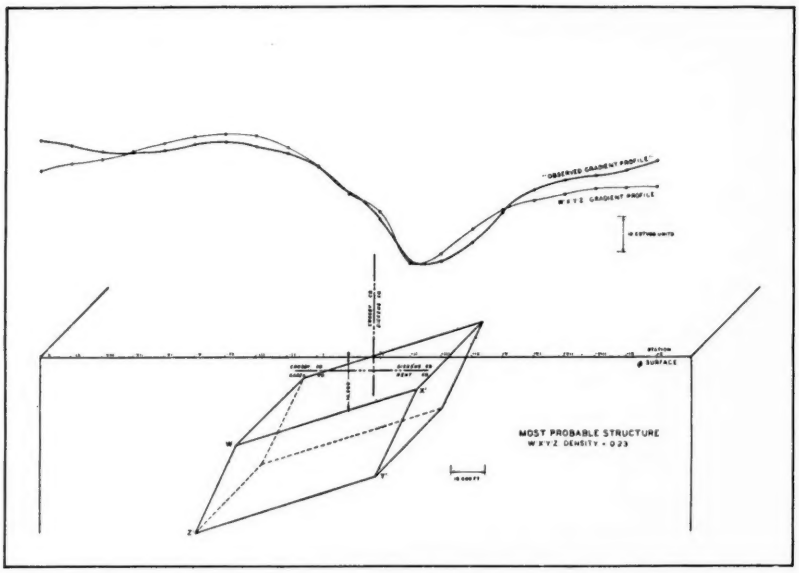


FIG. 10. Most probable structure; in perspective—with profiles.

Although these assumed masses as to shape, size, depth, and position are the only ones discussed here, many variations were calculated. Since many of the readers will be interested in the outline of the calculations of one of these profiles, and the numerical comparison of observed and computed gradient values, the summary computation table for the mass finally selected as the best fit (Fig. 10) is included.

GEOLOGICAL INTERPRETATION

The combination of a magnetic high and a gravity high in an area where the sediments were already known to have density at least the average of sedimentary rocks, suggests a basement rock of plutonic source, and that it was either a large monadnock or an intrusion into

SUMMARY COMPUTATION TABLE

W'X'Y'Z'
Obs./Cal.

Station	*Values* *Obs.*	*Cal.*	*Density*	*Cal.* *×0.23*	*d* *(dev.)*	d^2
+X	+ 6.2	− 6.8	−0.91	− 1.6	7.8	60.84
+IX	+ 3.6	− 8.2	0.4	− 1.9	5.5	30.25
+VIII	+ 1.9	− 11.3	—	− 2.6	4.5	20.25
+VII	+ 0.3	− 16.1	—	− 3.7	4.0	16.00
+VI	− 2.2	− 22.7	—	− 5.2	3.0	9.00
+V	− 8.3	− 34.6	—	− 8.0	0.3	0.09
+IV	−17.2	− 58.0	0.3	−13.3	3.9	15.21
+III	−22.7	− 90.4	0.25	−20.8	1.9	3.61
+II	−22.3	−103.0	0.21	−23.7	1.4	1.96
+I	−10.5	− 35.0	0.29	− 8.1	2.4	5.76
0	− 3.2	− 14.4	0.22	− 3.3	0.1	0.01
−I	+ 4.5	+ 19.1	0.23	+ 4.4	0.1	0.01
−II	+ 8.0	+ 42.8	0.18	+ 9.8	1.8	3.24
−III	+10.0	+ 56.8	—	+13.1	3.1	9.61
−IV	+11.3	+ 59.1	—	+13.6	2.3	5.29
−V	+10.9	+ 56.5	—	+13.0	2.1	4.41
−VI	+ 9.0	+ 47.4	—	+10.9	1.9	3.61
−VII	+ 8.2	+ 38.1	—	+ 8.8	0.6	0.36
−VIII	+ 8.5	+ 26.6	—	+ 6.1	2.4	5.76
−IX	+10.3	+ 22.2	—	+ 5.1	5.2	26.01
−X	+11.8	+ 15.5	—	+ 3.6	8.2	67.24

Least Square Sum = 288.52

the sedimentaries. The #1B Swenson found granite at a depth of −5810 feet subsea, which was within 40 percent of the depth to the plutonic rock calculated on Fig. 10, at the point where the well was drilled. The #1C Swenson did not reach granite at 5936 feet subsea, showing that the mass is dipping to the west, as was calculated on Fig. 10.

It would not have been expected that granite could give such density contrast with the limestones and shales above it as is actually found, and this would suggest that the granite is not the main constituent of the plutonic mass, but that the mass is principally a more basic rock than granite. Since the #1B Swenson drilled only 19 feet into the mass, we have no confirmation of this deduction.

A THEORY OF THE DISTRIBUTION OF RADIOACTIVITY IN MARINE SEDIMENTARY ROCKS*

PAUL WEAVER†

ABSTRACT

Gamma-ray measurements of marine sedimentary rocks indicate that in general the slower the rate of deposition the greater the radioactivity. The most recent measurements of the radioactivity of sea water suggest an increase with depth, which indicates a very slow settling of small particles. It is believed that a geologic time-scale of sedimentation can be established, subject to certain corrections due to fixation of radioactive minerals by organisms.

Rays are emitted when there is a transformation from one radioactive element to another. The elements which possess this property naturally are potassium, rubidium, and the elements of the three radioactive series—uranium, actinium, and thorium. The rays are of three classes, alpha-, beta-, and gamma-, and for each element the rays are specific as to frequency of emission and as to penetrating power through different media, therefore the number of gamma-rays, for example, which arrive at a point inside a well is dependent upon the kind of element which emits the rays, the distance of the emittor-atom from the observation point, and the absorbing power of the medium between, which may be drill mud or other fluid in the well, casing, or geological formation.

Certain gamma-rays are very penetrating, and therefore the kind of fluid in the well, presence or absence of casing, etc., reduce the proportion of the rays which arrive inside the hole only slightly, so that variation of their frequency from one point to another is proportional to the change in percentage, within the strata alongside the wall of the well, of a radioactive element or elements.

Apparatus has been inserted in a number of wells within recent months, whereby, with a connection to a recording device at a surface, a record or "log" can be made of the variation with depth of the total of the gamma-rays which originate in the drill mud or other fluids in the well and of those which are emitted from the strata forming the wall of the well. The apparatus which has been used is either a (1) Geiger-Mueller Counter or (2) Ionization Chamber. The Geiger-Mueller Counter set-up was described in GEOPHYSICS[1].‡

* Presented at the Annual Meeting, Houston, Texas, April 2, 1941.

† Gulf Oil Corporation, Houston, Texas.

‡ Figures refer to references at end of article.

There are other methods which are being used to measure the proportion of radioactive elements in rock or soil, which are not readily adaptable to use for logging wells, and are principally applied in the laboratory to hand specimens. These determine one of the following:

(1) Amount of alpha-rays from a gaseous radioactive element, either thoron or radon, or both from which the parent element is computed on equilibrium assumption.
(2) Amount of helium present, from which is computed total emission during past geologic time on assumption that helium is all derived from radioactive disintegration.
(3) Ratio of various isotopes of lead, since some of these are end products of radioactive disintegration.
(4) Velocity of beta-rays which are specific for each radioactive element.
(5) Secondary radiations emitted by exposure to a radioactive source. This method has recently been applied to well-logging.[2]

Since there is such a spectrum of rays due to the many radioactive elements in each of the three families of uranium, actinium and thorium, and since they are usually all present in many minerals found in sedimentary rocks, the values determined by the different methods are not convertible to those measured by the Geiger-Mueller Counter or the ionization chamber run into a well, nor are gamma-ray well logs precisely expressible in any unit to correct to a chemical formula expressing the kinds and proportions of each radioactive element present in the strata. It will be the purpose of this paper, however, to show that practically the readings of these logs have a definite interpretation, and to propose a theory that the variation in these readings from one kind of sedimentary rock has an application which gives the geologist a new time-scale.

It is already recognized that gamma-ray logs are useful to show the boundaries between different kinds of marine sedimentary rocks and for correlation between wells some distance apart.* The results of many wells are concordant in their pictures of the four great types of marine sediments. These are—(1) muds, clays and shales; (2) sands, sandstones and quartzites; (3) calcareous oozes, limestones, dolomites and chalks; (4) evaporites—salt, anhydrite and some limestones and dolomites. The relative gamma-ray intensity of these are as follows:—

* In some publications, a log by the use of the ionization chambers has been called a "Radioactivity log." Gamma-ray is a more precise term, and also has priority (see Reference (1)). It is hoped that the commercial operators will return to the "Gamma-ray" to identify logs made by ionization chambers.

Evaporites	lowest
Sands	low
Clays	high
Limestones	usually low, occasionally quite high.

Where measurements are made from surface samples for correlation with wells, there will be discrepancies unless fresh samples are used. Surface work on radioactivity content where the soil processes have begun will generally give higher values than characteristic of the formation because weathering results in an increase in the more insoluble rock minerals, among which are those with the radioactive elements as a constituent.

The marine sedimentary deposits of the present oceans have been studied by bottom samples taken by dredging and by coring. The muds accumulate on the bottom by flocculation of kaolin and similar colloids by the sea water; the sands by mechanical transport due to wave action; the lime oozes by decrease in carbon dioxide in the water and by action of organisms; and the evaporites are produced by precipitation when the ocean water has been concentrated by evaporation —anhydrite when 70% of the original water is evaporated, salt when 90% has been evaporated.

Geologists have speculated concerning the rate of sedimentation in the ocean, using various methods based on the rate of transport into the ocean by rivers and other physical factors. Some recent values are as follows, expressed in thickness after compaction:—

Shales	1 foot per 900 years[3]
Sandstones	1 foot per 450 years[3]
Limestones	1 foot per 2250 years[3]
Evaporites	1 foot per 3 years[4].

There is no unanimity concerning the numerical values given above or even the order of magnitude, as the methods used by different geologists to calculate them have been based on different processes. However, there is agreement as to the general relation expressed above, that evaporites form very much faster than any other type of sediment; sandstones are faster in rate of deposition than shales which again are faster in rate of deposition than limestones.*

* Limestones are the present form not only of what were originally calcareous oozes, but of evaporites, of clastics made of lime fragments, of coquina beds, and of secretions of organisms. Only as to the limestones formed from calcareous oozes, can we use the rate of deposition mentioned. Where other conditions are present, limestone source material may be deposited very rapidly.

It will be observed that the geologist has estimated a comparative time-scale for the deposition of the three classes of marine sediments—muds, sands and evaporites, according to which they are arranged in the same order that these classes respond to gamma-ray logging, that is, the faster the rate of deposition estimated by the geologist, the less the gamma-ray reading. Interestingly enough, this is outstanding in the case of halite, or common salt, the principal evaporite, which is the least radioactive of all rocks known—in fact, the best place in the world to calibrate a Geiger-Mueller counter is in a salt mine, provided the salt is pure or nearly so, as has been recognized before there was any gamma-ray logging.

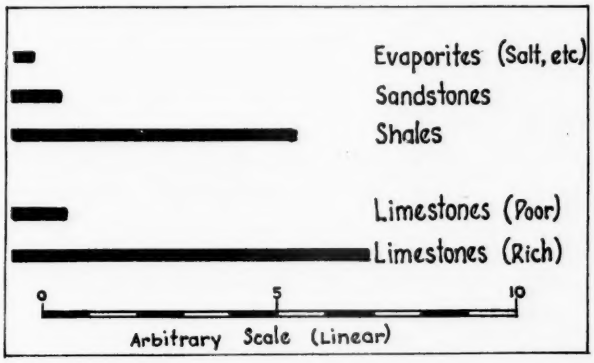


FIG. 1. Relative Gamma-Ray Activity of Sedimentary Rocks.

There is much evidence in literature of measurements of the radioactivity of sedimentary rocks taken on hand specimens in the laboratory and on soils overlying the rocks, taken in the field, but a recapitulation seems unnecessary, first, because the technique was not always standard and precise; and second, because the logging of thousands of feet of drilled wells is equivalent to many thousand times all the other data. However, the author is satisfied that the relative radioactivity of the four classes of sediments from all the evidence is substantially as shown in Fig.1.*

* Sediments contain locally special mineral zones. For example, a sandstone deposited near an old land mass of pre-Cambrian rocks will have much heavy minerals and therefore may be exceptionally high. Phosphate nodules in shales and limestones may be radioactive due to replacements of base radicles by radium, etc. Such special conditions are quite useful for geologic correlations, giving sharp, narrow peaks on the gamma-ray logs, but are not characteristic of thick zones.

Assuming an inverse correlation therefore between rapidity of sedimentation in the ocean and degree of radioactivity in the sediments, there is naturally a query as to the cause. If we can find this cause in some physical process in the ocean water, we may be able to measure it in operation today and obtain a numerical conversion factor from gamma-ray reading to years per foot of deposition, after gamma-ray variations have been calibrated so that logs taken under different operating conditions are comparable.

Now how do the radioactive elements occur in the ocean? Recent measurements[5] show that the radioactive content of sea water is quite low, but increases with increasing depth at greater than a linear rate. It is also evident that in the deep quiet bottoms, far from land and where wave action is minimized, the oozes on the ocean bottom have very high radioactivity compared either to the average of all oceanic sediments or to the sea water in contact with them. The author proposes that these observations support a theory that the mechanism of accumulation of radioactive minerals is the sedimentation of very small discrete particles of the parent elements in mineral combination falling from the air through the sea water to the bottom at a rate which is statistically constant. A certain amount of these particles is dissolved enroute, a larger amount is fixed temporarily by organisms which are strongly selective, such as kelp, but the total effect of all of these interruptions to the downward settling of the particles is considered of second order, because of the very small solubility and of the relative paucity of the selective organisms.

What is the source of the mineral particles assumed to be slowly settling? They can come only from four sources: (1) river muds of extreme fineness and stable in sea water; (2) volcanic dust from eruptions; (3) meteor clouds; (4) general dust circulation in larger wind movements. River muds and volcanic dusts would be locally concentrated and should result in areas of very high radioactive sediments irrespective of whether they be shales or sandstones or evaporites. Perhaps more widespread application of the gamma-ray log will show such areas, but they are not now known. Only general wind circulation and meteor clouds are widely enough distributed in time and space to give uniform conditions over large areas. Meteors were for many years considered non-radioactive, but recently it has been reported that some are. However, the total tonnage which falls annually into the atmosphere and reaches the earth's surface unconsumed, is small, and the size of individual fragments probably too large for slow sedimentation in the ocean.

Therefore there seems left as the source for the particles of radioactive material only the general air circulation carrying the finest particles derived by wind action (aerial erosion) on the land surface. This material would be of small diameter. It would contain principally those minerals of low solubility in water vapor, of considerable hardness, and of a greater proportion of heavy minerals than the average of the earth's crust, because it was derived principally from residual soils rather than from fresh rock. Such properties are those which would supply in relative abundance the zircon, monazite, etc., in which heavy elements are most frequent.

If this dust from general air currents be the source of the radioactive minerals, its rate of supply to the surface of the ocean would be expected to be statistically constant over a geological unit of time. Its rate of sedimentation through the sea water would also be constant because biological data indicates constancy of composition, viscosity, temperature of sea water at different depths through long periods of time.

The best check on this hypothesis would be the collection of large samples of atmospheric dust and their radioactive analysis, also a statistical investigation of grain size and mineral composition, so that a computation could be made of the rate of sedimentation and loss by solution in sea water. These figures compared with radon now in solution in sea water would check the general theory for the uranium family. Similar measurements for the thorium family would be somewhat more difficult, but not impossible. As far as present literature is concerned, the evidence does not seem to be forthcoming for a first numerical calculation.

This theory is worth investigation for several reasons. In the first place, it would indicate that limestones are poor for correlation of geologic time, and that there are different limestones with different histories. The limestone reservoirs are important as oil producers, and are puzzling in their rapid areal variations (reefs).

Again, when a shale thickens from one well to another, there is now uncertainty as to whether the difference is due to variation in amount of supply of the original mud, or whether there has been downwarping so that more deposition time was involved where the shale is thicker. The establishment of downwarping as the cause of the thickening would help the search for stratigraphic traps, if used in connection with isopach maps made by the reflection seismograph.

Finally, the establishment of a geologic time-scale for sediments will help in studies of compaction and regional metamorphism, especially

in monoclines and geosynclines, which are the tectonic provinces of most of our oil fields. There might even be cases where the paleontological correlations could be checked over some distance.

REFERENCES

(1) Howell, Lynn G. and Frosch, Alex. Gamma-Ray Well-Logging. GEOPHYSICS, vol. IV, 2, March, 1939, pp. 106–114.
(2) Pontecorvo, B. Neutron Well-Logging. Oil & Gas Journal, Sept. 11, 1941, pp. 32–33.
(3) National Research Council, Age of the Earth (volume IV of Physics of the Earth, Bull. 80), March, 1931, page 13.
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(5) Evans, R. D., Kip, A. F., and Moberg, E. G. The Radium and Radon Contents of Pacific Ocean Water, Life and Sediments. Amer. Jour. Sci., 5th series, 214, Vol. 36, Oct. 1938, pp. 241–259.

A complete set of abstracts of current literature appears in the annual reports of the Committee on Geologic Time of the National Research Council, Washington, D. C.

DISCUSSIONS AND COMMUNICATIONS

WAR EFFORTS ADVISORY COMMITTEE

At the annual meeting of the Society in Denver on April 24, 1942, a resolution proposed by B. B. Weatherby was unanimously adopted by those present as follows:

Resolved, That the Society of Exploration Geophysicists cooperate fully in the War Effort of our country by aiding in every possible way the maintenance of an adequate exploration program and also further the placement of all available geophysical personnel in suitable positions with the armed forces and other governmental agencies; also that the Society render assistance to all geophysical laboratories and shops desiring to do work for the government and for these purposes a committee be appointed by the President.

To put into effect this resolution the President, Dr. Peacock, immediately appointed a committee to be known as the War Efforts Advisory Committee. Those appointed were the following: B. B. Weatherby—Chairman, Henry C. Cortes, R. D. Wyckoff, Herbert Hoover, Jr., W. G. Green and F. Goldstone.

At the time of going to press, it has not been possible to ascertain that all of these appointees will be able to serve but it is anticipated that a committee substantially as above will be functioning shortly. Accordingly, members who have problems which they believe fall within the scope of the activities of this committee should communicate with the chairman.

COMMITTEE ON EXPLORATION UNDER O.P.C.

On March 9, under the Production Committee for District 3, as defined by the Office of the Petroleum Coordinator, a subcommittee was organized, to be known as the Committee on Exploration, comprised of Messrs. Sidney A. Judson, Phil F. Martyn, R. R. Morse, Ed. W. Owen, Paul Weaver, and F. H. Lahee, chairman. This Committee on Exploration is a fact-gathering group of men, not representing any particular company association, or special interests, but serving as representatives of the petroleum industry. The function of the Committee is to assemble, as soon as possible, data bearing (1) on the progress of wildcatting (i.e., exploration for oil by drilling outside of known producing pools, or below the deepest known pay sands in producing pools); (2) on prospects for petroleum not yet exploited; (3) on methods of exploration to be used in search for new prospects; (4) on the quantity of steel needed in exploring for new prospects; and (5) on the quantity of steel needed for wildcat drilling for oil on new prospects.

An early and comprehensive study of these and related data is vital in the program of coordinating the petroleum industry for national defense. Therefore, it is expected that all persons and organizations approached for information toward this end will be ready to cooperate. The committee will welcome any constructive suggestions.

F. H. LAHEE, *Chairman*

PATENTS*

ELECTRICAL PROSPECTING

U.S. No. 2,268,106, L. W. Blau, Iss. 12/30/41, Appl. 5/13/39. Assign. Standard Oil Development Co.

Radio Wave Prospecting—A method of locating subsurface structures, particularly faults, by recording and mapping the field strength or combinations of field strengths of one or more distant radio transmitters.

U.S. No. 2,270,325, N. W. Matthews, Iss. 1/20/42, Appl. 1/18/41.

Auxiliary Electrode for Ground Resistance Measurement—A ground electrode having at its upper end two collars between which a weighted sliding handle may be used either to drive the electrode into the ground or to drive it out after use.

GEOCHEMICAL PROSPECTING

U.S. No. 2,257,170, L. G. Howell, Iss. 9/30/41, Appl. 12/27/34–1/21/38. Assign. Standard Oil Development Co.

Method for Locating Hydrocarbon Deposits in the Earth—A method for determining hydrocarbon gases in the soil by sucking soil gas from a shallow bore hole, passing the gas through a liquid which dissolves hydrocarbons, and then analyzing the liquid.

U.S. No. 2,269,889, L. W. Blau, Iss. 1/13/42, Appl. 2/27/39. Assign. Standard Oil Development Co.

Process for Locating Valuable Subterranean Deposits—A method of prospecting in which soil samples are tested with a reagent which produces a color change when applied to soil containing hydrocarbon consuming bacteria which have been subjected to action of hydrocarbons.

U.S. No. 2,270,299, L. Horvitz, Iss. 1/20/42, Appl. 3/23/39. Assign. E. E. Rosaire.

Geochemical Prospecting—A method of soil analysis involving treatment of soil samples with hydrochloric or other acid to dissolve carbonates and release trapped hydrocarbons.

U.S. No. 2,272,645, E. E. Rosaire, Iss. 2/10/42, Appl. 11/21/41.

Geochemical Prospecting—A method of geochemical prospecting in which shallow holes are treated with acid and the released gas pumped off and analyzed.

GRAVIMETRIC PROSPECTING

U.S. No. 2,262,165, D. H. Clewell, Iss. 11/11/41, Appl. 7/3/40. Assign. Socony-Vacuum Oil Co.

Gravity Meter—A null reading gravity meter in which the main spring is displaced transversely by an adjustable secondary spring so as to change the lever arm of the main spring.

U.S. No. 2,264,342, D. Silverman and J. L. Bible, Iss. 12/2/41, Appl. 5/12/39. Assign. Stanolind Oil and Gas Co.

Geophysical Instrument Mounting—A gravimeter mounting which eliminates removal of instrument from truck and affords protection in transit.

* Abstracts by O. F. Ritzmann, Gulf Research & Development Co.

SEISMOGRAPH PROSPECTING

U.S. No. 2,257,187, J. E. Owen, Iss. 9/30/41, Appl. 12/21/39. Assign. Geophysical Research Corporation.

Seismic Surveying—A method of eliminating ground roll from a seismic record which consists in combining with the output of the usual velocity type vertical geophone either the output of a displacement type horizontal instrument or an acceleration type horizontal instrument.

U.S. No. 2,259,478, C. G. Morgan, Iss. 10/21/41, Appl. 10/1/38. Assign. Consolidated Engineering Corporation.

Geophysical Exploration System—A method of seismic prospecting in which continuous control is obtained by shooting into a spread from regularly spaced shot points more distant than those adjacent to the spread.

U.S. No. 2,261,321, P. S. Williams, Iss. 11/4/41, Appl. 6/17/38. Assign. Standard Oil Development Co.

Seismic Exploration Method—A method to facilitate the identification of reflections on a seismic record by recording along with the customary traces one or more traces showing average rectified amplitude.

U.S. No. 2,263,519, O. F. Ritzmann, Iss. 11/18/41, Appl. 12/2/38. Assign. Gulf Research & Development Co.

Seismograph Prospecting Apparatus—Eliminating seismic interference falling within the useful range of frequencies by superimposing on the usual band pass filter a relatively sharper band absorption filter.

U.S. No. 2,264,596, E. M. Shook and R. W. Olson, Iss. 12/2/41, Appl. 10/23/40. Assign. Socony-Vacuum Oil Co.

Geophysical Instrument—Method of making seismic shot moment or other time breaks identifiable through static by having shooting device start a relaxation oscillator thus repeating the break at regular known intervals.

U.S. No. 2,265,513, K. E. Burg, Iss. 12/9/41, Appl. 6/10/39. Assign. Geophysical Service, Inc.

Prospecting Method and Apparatus—A method of seismic prospecting in which each detector is equipped with a radio transmitter and recording is accomplished via radio instead of cables.

U.S. No. 2,265,538, J. P. Minton, Iss. 12/9/41, Appl. 7/9/38. Assign. Socony-Vacuum Oil Co.

Gain Control for Seismograph Amplifiers—A manual gain adjusting circuit having a linear relation between gain and position of control index.

U.S. No. 2,265,768, L. F. Athy, H. R. Prescott and R. F. Hughes, Iss. 12/9/41, Appl. 7/20/40. Assign. Continental Oil Co.

Method of Logging Bore Holes—A seismic method of well logging making use of a continuous wave transmitter to set up standing waves and measuring the impedance changes as the transmitter is lowered down the well, also exploring the standing wave field with several vibration receptors lowered into the well with the transmitter.

U.S. No. 2,266,040, H. Hoover, Jr., Iss. 12/16/41, Appl. 9/16/37. Assign. Consolidated Engineering Corp.

Geophysical Prospecting Receptor Circuits—A seismic detector-amplifier input circuit having a shielded isolation transformer whose primary is balanced to ground and whose secondary may be interconnected to other channels to permit mixing.

U.S. No. 2,266,041, H. Hoover, Jr., Iss. 12/16/41, Appl. 4/18/38. Assign. Consolidated Engineering Corp.

Geophysical Prospecting Receptor Circuits—A seismic detector-amplifier input circuit having two shielded transformers in cascade, the primary being balanced to ground and the intermediate circuits being interconnected and adjustable to eliminate cross-feed and permit controlled mixing.

U.S. No. 2,266,837, H. F. Wiley, Iss. 12/23/41, Appl. 7/24/39. Assign, Consolidated Engineering Corp.

Method and Apparatus for Translating Seismic Waves—A geophone whose weight and base area are so proportioned that the frequency of maximum response when planted is above the frequency range of reflections.

U.S. No. 2,267,357, O. F. Ritzmann, Iss. 12/23/41, Appl. 1/16/40. Assign. Gulf Research & Development Co.

Apparatus for and Method of Seismograph Recording—A method of mixing seismograph channels optically by having the recorded light beam reflected successively from two galvanometers.

U.S. No. 2,267,858, C. H. Dix, Iss. 12/30/41, Appl. 9/8/41. Assign. Socony-Vacuum Oil Co.

Method of Seismic Surveying—A method of refraction profiling which requires shooting in only one direction.

U.S. No. 2,268,130, M. M. Slotnick, Iss. 12/30/41, Appl. 2/8/40. Assign. Standard Oil Development Co.

Method of Geophysical Investigation—A method of outlining a subsurface structure by placing a seismic detector in a well penetrating the structure and shooting into it from shot points on the surface.

U.S. No. 2,269,453, E. L. Gayhart, U.S.N., Iss. 1/13/42, Appl. 1/12/38.

Device for Detecting Displacements—A displacement meter or seismometer in which a coil moves in an alternating magnetic field so that the alternating current induced is proportional to the displacement.

U.S. No. 2,269,890, L. W. Blau, Iss. 1/13/42, Appl. 9/30/39. Assign. Standard Oil Development Co.

Seismic-Electric Prospecting—Seismic-electric detectors consisting of two current electrodes and one or more pairs of potential electrodes at stations where it is desired to pick up seismic disturbances.

U.S. No. 2,271,864, P. M. Honnell and L. W. Dickerson, Iss. 2/3/42, Appl. 6/10/38. Assign. The Texas Co.

Seismic Wave Detector—A suspended coil electromagnetic geophone provided with electromagnetic and electrostatic shielding.

U.S. No. 2,272,741, T. E. Failing, Iss. 2/10/42, Appl. 2/28/38. Assign. George E. Failing Supply Co.

Apparatus for Seismic Surveying—A non-metallic non-resonant shot hole casing which eliminates transmission of shock up the casing.

U.S. No. 2,272,984, O. F. Ritzmann, Iss. 2/10/42, Appl. 7/21/39. Assign. Gulf Research & Development Co.

Seismograph—A geophone having a band pass response characteristic which consists of two suspended masses with different resonant frequencies and a transducer whose output depends on the difference of their individual response characteristics.

WELL LOGGING AND SURVEYING

U.S. No. 2,261,563, F. Rieber, Iss. 11/4/41, Appl. 2/18/39.

System for Measuring Earth Conductivity—A method of electric well logging while drilling by passing an alternating current between the drill stem and a distant surface electrode and measuring by a null method the magnetic field created at a third point on the surface.

U.S. No. 2,262,419, L. F. Athy and H. R. Prescott, Iss. 11/11/41, Appl. 4/9/38. Assign. Continental Oil Co.

Method of Electromagnetic Logging—A well logging method using surface current electrodes on each side of the well and a nondirectional horizontal magnetic field detector lowered into the well.

U.S. No. 2,265,978, D. E. Batchelder, Iss. 12/16/41, Appl. 10/4/39. Assign. Lane-Wells Co.

Alternating Current Electro-Logging of Well Bores—An A. C. well logging method in which simultaneous curves are drawn of the in-phase potential, quadrature potential and phase angle.

U.S. No. 2,266,071, R. G. Piety, Iss. 12/16/41, Appl. 5/31/39. Assign. Phillips Petroleum Co.

Well Surveying Device—A method of electric well logging using a surface electrode and a very long wire electrode in the well and measuring the current distribution leaving the wire by interposing a sliding shielding electrode connected to a meter.

U.S. No. 2,268,137, H. M. Evjen, Iss. 12/30/41, Appl. 12/11/39. Assign. Shell Development Co.

Electrical Well Logging System—A four electrode method of logging uncased holes which makes a sequence of A.C. and D.C. measurements controlled by synchronous commutators so as to obtain three log curves simultaneously.

U.S. No. 2,268,138, H. M. Evjen, Iss. 12/30/41, Appl. 12/11/39. Assign. Shell Development Co.

Electrical Well Logging System—A four electrode method of logging uncased holes

which simultaneously gives the limited and extended radius resistivity (A.C.) curve and also the spontaneous (D.C.) potential curve.

U.S. No. 2,268,256, W. S. Knouse, Iss. 12/30/41, Appl. 2/3/40. Assign. 1/2 to National Lead Co.

Apparatus for Surveying Deep Wells—A geometrical well surveying instrument using an opaque liquid to change the amount of light falling on three photo cells for determining inclination and a shaded compass card to change the amount of light falling on a photo cell for determining direction.

U.S. No. 2,268,627, D. Silverman, Iss. 1/6/42, Appl. 10/6/39. Assign. Stanolind Oil and Gas Co.

Well Logging—A method of well logging using a drilling fluid under high pressure, substituting a liquid having a different physical or chemical property, releasing the pressure to allow drilling fluid to reenter the well, and measuring the chemical or physical property at various levels in the well.

U.S. No. 2,268,682, E. R. Webb, Iss. 1/6/42, Appl. 10/9/37. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Instrument—An inclinometer using a pendulum and recording by means of an electric spark.

U.S. No. 2,269,269, F. W. Jessen, Iss. 1/6/42, Appl. 7/15/40. Assign. Standard Oil Development Co.

Well Logging—A method of locating breaks or ends in casing which consists in lowering a galvanic electrode into the well and measuring the potential between this electrode and the casing.

U.S. No. 2,269,573, A. Barry, Iss. 1/13/42, Appl. 4/29/39. Assign. Standard Oil Development Co.

Adjustable Measuring Wheel—A well logging cable or wire line measuring wheel having adjustable circumference.

U.S. No. 2,269,717, D. Hering, Iss. 1/13/42, Appl. 12/13/40. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Device—An inclinometer in which colored ink marks a cylindrical record so arranged that the ink need not be removed between runs.

U.S. No. 2,271,951, J. M. Pearson and G. A. Smith, Iss. 2/3/42, Appl. 2/12/36, Assign. Sperry-Sun Well Surveying Co.

Electrical Prospecting Method and Apparatus—A well logging apparatus which records in the hole the effect of surrounding formations on a high frequency oscillating circuit.

U.S. No. 2,273,215, J. Neufeld, Iss. 2/17/42, Appl. 4/22/40. Assign. Well Surveys, Inc.

Well Surveying Method and Apparatus—A method of determining the point of entry of formation fluid into a cased hole by making repeated radioactivity logs under reduced hydrostatic pressure.

U.S. No. 2,273,363, E. Lipson, Iss. 2/17/42, Appl. 11/28/39.

Method for Electrical Investigation of Cased Drill Holes—A four electrode method of electrical well logging using two electrodes on the surface and using current values which are disproportionate to the potential, e.g., 0.2 to 1.0 amp.

MISCELLANEOUS

U.S. No. 2,268,808, J. O. Davis, Iss. 1/6/42, Appl. 12/6/39. Assign. Henry Hughes & Son, Ltd.

Recording Device—A stylus type recorder for echo sounding having devices for changing speed, zero correction and phasing adjustments.

U.S. No. 2,269,414, J. P. Woods, Iss. 1/6/42, Appl. 10/16/39. Assign. Shell Development Co.

Multiple Recording Galvonometer—A permanent magnet oscillograph unit having elements mounted in separately removable cartridges and using a condensing lens to concentrate light on the galvanometer mirrors.

CONTRIBUTORS

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DAYTON H. CLEWELL received his B.S. degree in 1933 and his Ph.D. degree in 1936, both from the Massachusetts Institute of Technology. He was employed by the C. K. Williams Company of Easton, Penna., from 1935 to 1938 as a physicist working on optical problems associated with pigments. Since 1938 he has been associated with the Geophysical Laboratory of the Magnolia Petroleum Company where he has been concerned mainly with the development of gravimeters. He is the author of three papers in the field of experimental physics. He is a member of the American Physical Society and of Sigma Xi.

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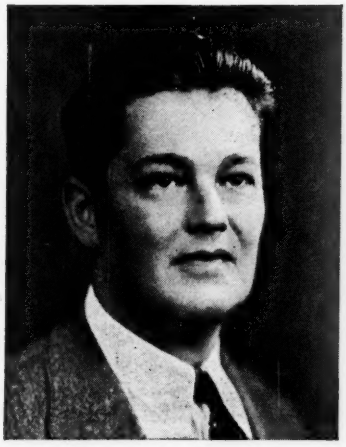

RAYMOND G. PIETY

RAYMOND G. PIETY received his B.S. degree from the University of Chicago in 1932 and his Ph.D. in Physics from Yale in 1936. He was engaged in sound motion picture development for Warner Brothers Pictures, Inc. during 1930 and 1931 and again during 1935 and 1936. He joined the research staff of the Phillips Petroleum Company in 1937 where he is still employed. His work as section chief in charge of geophysical research has been largely concerned with problems of instrument development. He is a member of the American Physical Society and the Society of Exploration Geophysicists.

JOSEPH A. SHARPE

JOSEPH A. SHARPE received his B.S. degree in physics from the University of Arizona in 1928, and his Ph.D. degree in physics from the University of Wisconsin in 1934, after which he spent one year at the Massachusetts Institute of Technology as a General Education Board (Rockefeller Foundation) fellow in geophysics. He has been associated with the joint geophysical laboratory of the Stanolind Oil and Gas Company and the Western Geophysical Company since 1935, first as seismologist, and, since 1937, as chief physicist. Dr. Sharpe's work has been primarily concerned with the initiation, propagation, and characteristics of elastic waves, although he has also worked on seismic and geomagnetic instrumentation and interpretation, and on gravity interpretation. He is a member of the American Physical Society, the American Mathematical Society, the American Association of Petroleum Geologists, the Society of Exploration Geophysicists, the American Geophysical Union, the Seismological Society of America, and the Tulsa Geological Society.

NEIL R. SPARKS received his B.S. degree in Electrical Engineering from the University of California, Berkeley, in 1932. He continued his graduate studies in the field of Seismology until 1933 at which time he entered the employ of the U. S. Coast and Geodetic Survey in their program of earthquake research. Since 1936 he has been associated with the Western Geophysical Company and the Stanolind Oil and Gas Company in their combined Geophysical Laboratories. Mr. Sparks' work has been primarily the interpretation of seismic data. He is a member of the Seismological Society of America and the Society of Exploration Geophysicists.

NEIL R. SPARKS

REVIEW

Geophysics in War, by C. A. Heiland, Professor of Geophysics, Colorado School of Mines. Published in Vol. 37, No. 1 of the Colorado School of Mines Quarterly. Price $1.00 postpaid.

The science of geophysics is concerned with the physical phenomena in and the transmission of energy through the earth, the water, and the air. Its applications in war and preparation for war fall into two groups: military operations, and the location of essential minerals.

In the combat zone acoustic triangulation or sound ranging helps to locate hostile guns. Listening devices determine the approach of submarines or airplanes. Sound-ranging methods are also employed in establishing the range of friendly artillery. Land and sea mines may be controlled by radio and acoustic impulses. Buried munition dumps, shells, and bombs can be located by the radio detection devices. Communication between battlefleet vessels is often maintained by sonic and supersonic transmission. Position finding at sea is facilitated by radio-acoustic ranging. In periods of poor visibility vessels may navigate by echo depth sounding. A similar application is terrain-clearance determination by high-frequency radio from a plane.

Planning of fortifications (gun emplacements, shelters, harbors) and the location of construction materials for them will be aided by seismic refraction, electrical resistivity, and dynamic ground testing. The same methods are used in all kinds of transportation problems involving the construction of railroads, highways, bridges, tunnels, etc., and in the planning of munitions plants. For the last, added protection may be afforded by static-ground-resistance investigations.

Meteorology, an important part of geophysics, is applied in weather forecasting for military operations, maneuvers, in sound ranging, and acoustic airplane spotting. Data on rainfall, humidity, and flood frequency are useful in the planning of certain defense plants. Salvage operations, particularly the location of shipwrecks and practice weapons, are aided by echo-sounding and radio location methods.

The second group of geophysical applications is concerned with the location of mineral resources, comprising water, fuels, and strategic minerals. Water may be located under favorable conditions by electrical and seismic geophysical methods; salt-water contamination may be traced, and water wells may be tested by electrical logging. Geophysical methods mentioned before in connection with foundation investigations are applicable to water-control problems arising in connection with irrigation, flood-control, and power projects. Of vital importance in modern warfare is an adequate supply of petroleum. Geophysical exploration by magnetic, gravimetric, seismic-reflection, and electrical well-logging methods occupies a prominent place in the oil industry. Coals and lignite deposits may be mapped by geophysical methods. Magnetic, electrical, gravimetric, and seismic exploration methods are now widely used in a systematic, government-sponsored exploration program to uncover vitally needed deposits of bauxite, chromite, manganese, mercury, nickel, tin, and tungsten.

THE SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Robert Frank Aldredge
G. H. Westby, T. A. Manhart, A. J. Barthelmes

Gerald Allan Burton
H. R. Thornburgh, W. Hafner, Harry L. Thomsen

Cecil Edmund Chesher
W. Hafner, H. R. Thornburgh, Harry L. Thomsen

C. Calhoun Cody, Jr.
G. H. Westby, T. A. Manhart, A. J. Barthelmes

Jesse Robert Cornett
G. H. Westby, T. A. Manhart, A. J. Barthelmes

James Edward Dorris
G. H. Westby, T. A. Manhart, A. J. Barthelmes

Laurence Meade Hubby
George D. Mitchell, Jr., C. C. Zimmerman, Roy L. Lay

Phillip John Kempsky
W. T. Born, L. Y. Faust, B. B. Weatherby

Theodore Koulomzine
(Article III-D-1 of the Constitution)

W. Warren Longley
(Article III-D-1 of the Constitution)

John Joseph Lynch S. J.
James B. Macelwane, S. J., Louis B. Slichter, Cornelius G. Dahm

John William Marston
G. H. Westby, T. A. Manhart, A. J. Barthelmes

Haydon Wilburn McDonnold
George D. Mitchell, Jr., Roy L. Lay, C. C. Zimmerman

Jacob Neufeld
W. G. Green, T. A. Manhart, Alexander Wolf

Albert Clark Reid
Joseph A. Sharpe, Daniel Silverman, Jack R. Cooper

George Hendricks Speirs
G. H. Westby, T. A. Manhart, A. J. Barthelmes

Edward Banks Stover, Jr.
Joseph A. Sharpe, Jack R. Cooper, Neil R. Sparks

Joel Howard Swartz
J. Brian Eby, James B. Macelwane, S. J., C. E. Van Orstrand

John Gordon Cole
Cecil H. Green, Phil P. Gaby, Frederick Romberg
Larkin Earl Deacon
F. Goldstone, Willy Hafner, M. O. Gibson
Stuart Sawyer Giezendanner
George D. Mitchell, Jr., Roy L. Lay, C. C. Zimmerman
Otto George Holekamp
F. Goldstone, W. Hafner, M. O. Gibson
Ford Lawrence Johnson
H. W. Rose, W. G. Smiley, Jr., L. G. Ellis
Henry Leonhard Rase, Jr.
Paul F. Clement, Herbert J. Ferber, Victor J. Pezdek
Rudolph Gust Sohlberg
F. E. Romberg, C. H. Green, K. E. Burg
David McIntosh Steel
T. R. Shugart, E. E. Wilson, H. Hallock Brown
Thomas Scott West
Cyril B. Smith, F. Goldstone, David S. Muzzey, Jr.

TRANSFER TO ACTIVE

W. T. Lea
J. B. Meitzen
Edward C. Reagor
Harry H. Sisson

ASSOCIATE

Robert Wiley Adams
Joseph LaConte, John W. Mathews, T. P. Ellsworth

STUDENT

Ralph Theodore Duffner
W. S. Levings, R. Maurice Tripp, Dart Wantland
Benjamin Franklin Howell, Jr.
Beno Gutenberg
Kennedy Robert Marble
Dart Wantland
Louis Charles Pakiser, Jr.
Dart Wantland

PERSONAL ITEMS

DWIGHT E. WARD, formerly with the Carter Oil Company, has accepted foreign employment with the International Petroleum Company, P. O. Box 803, Guayaquil, Ecuador, S. A.

GEORGE H. WESSLER, JR., associate member of the Society with N. K. P. M. in the Netherlands East Indies upon the outbreak of the Pacific war, is reported to have joined the U. S. Army.

C. T. RANKIN should be addressed c/o Geophysical Research Corporation, P. O. Box 2040, Tulsa, Oklahoma.

ROBERT BARLING, formerly with the Western Geophysical Company, is now Chief Geologist and Engineer for the Miller Geophysical Company of Los Angeles, California. He is located at 830 18th St., Bakersfield, California.

D. G. EGAN has returned from the Netherlands East Indies and is located in Crowley, Louisiana, with the mailing address P. O. Box 366.

HORACE S. MOORE is serving as Field Draftsman and Instrumentman with the Southwestern Engineering Company of Los Angeles. He may be addressed at 2204 Floral Drive, Whittier, California.

EDWARD S. FOSTER, JR., Well Logging Operator with the Halliburton Oil Well Cementing Company, is located at 604 Madison Street, Lafayette, Louisiana.

C. H. DIX is now Acting Chief Seismologist with the United Geophysical Company, 1255 East Green Street, Pasadena, California.

MALCOLM S. MORRISON, Geophysicist with the Gulf Research and Development Company, should be addressed at Box 1342, R. D. 1, Frankstown Road, Wilkinsburg, Pennsylvania.

KENNETH E. BURG has resigned from Geophysical Service, Inc. to accept a position as Technical Supervisor with the Stanolind Oil and Gas Company, Philcade Building, Tulsa, Oklahoma.

GEORGE A. GARRETT, formerly with the Independent Exploration Company, is acting as Research Associate in the Radiation Laboratory of the Massachusetts Institute of Technology in Cambridge. His mailing address is 81 Elm Street, Belmont, Massachusetts.

STANLEY W. WILCOX, of Seismograph Service Corporation, should be addressed at 709 Kennedy Building, Tulsa, Oklahoma.

WALTER D. BAIRD, Computer with Geophysical Service, Inc., is now located at P. O. Box 391, Fresno, California.

J. M. KILBORN, Magnetometer Party Manager with the Gulf Research and Development Company, is located in Lubbock, Texas, with the mailing address P. O. Box 1436.

News Letter No. 4 of the U. S. Waterways Experiment Station, P. O. Box 631, Vicksburg, Mississippi, lists "Subject-Headings for Material in Engineer Department Research Centers Library." It is noted that printed matter, slides, and films may be obtained on a thirty-day loan basis by individuals connected with reputable firms or institutions.

E. W. JOHNSON is acting as Seismograph Observer for the Cities Service Oil Company, Bartlesville, Oklahoma.

L. B. SLICHTER is serving on the National Defense Research Committee of the Office of Scientific Research and Development, 10th Floor, 172 Fulton Street, New York, N. Y.

JOHN W. TEXTER has returned from foreign employment and is doing seismograph interpretation with the Gulf Research and Development Company, P. O. Drawer 2038, Pittsburgh, Pennsylvania.

LT. G. W. HOSTETLER, formerly with the Petty Geophysical Engineering Company, is located in the Signal Corps General Developmental Laboratories, Fort Monmouth, Red Bank, New Jersey.

AUSTIN N. STANTON is President of Petroleum Science, Inc., with offices in the Kirby Building, Dallas, Texas.

VINCENT J. MERCIER, of the Lane-Wells Company, has the mailing address P. O. Box 221, Seminole, Oklahoma.

W. E. WALLIS has accepted foreign employment with the West India Oil Company, Apartado XXIII, San Jose, Costa Rica.

On March 14th, the Rice Chapter of Sigma Xi invited Houston physicists and engineers to attend the annual lecture, presented by Dr. Percy W. Bridgman, Hollis Professor of Mathematics and Natural Philosophy of Harvard University. The subject was "Some Recent Work in the Field of High Pressures."

GEORGE B. SOMERS has advised the Society of his transfer to the Naval Bureau of Ordnance. As he is continually on the move, correspondence should be addressed to his home, 4336 Bowser Avenue, Dallas, Texas.

GEORGE N. MEADE is serving as Jr. Seismograph Observer for the Magnolia Petroleum Company, Box 900, Dallas, Texas.

R. W. LINDSEY, Geophysicist with the Gulf Research and Development Company, is located at P. O. Box 213, New Orleans, Louisiana.

LT. R. G. PATERSON, R. C. N. V. R., should be addressed c/o Naval Officer in Charge, Vancouver, B. C., Canada.

H. WAYNE HOYLMAN, of the Gulf Research and Development Company, is on foreign duty at Puerto Cabezas, Nicaragua.

H. M. ZENOR has left the Humble Oil and Refining Company to accept employment with the Sperry Gyroscope Company, Inc., Clinton Road and Stewart Avenue, Garden City, New York.

P. M. KONKEL, of the Ohio Oil Company, has been transferred from Rochester, Indiana, to Marshall, Illinois.

RAYMOND LAWRENCE SARGENT resigned from the Amerada Petroleum Corporation on March 23rd to accept a position as Chief Computer on Crew 20 of the National Geophysical Company, Tower Petroleum Building, Dallas, Texas.

CORPORAL CHARLES C. BATES, formerly with the Carter Oil Company, is on duty with Battery A, 2nd F. A. Obsn. Bn., Camp Bowie, Texas, as Chief Computer in the Sound Plotting Squad.

DONUIL HILLIS is now serving as Geologist with the Capital Company, 1 Powell Street, San Francisco, California.

F. F. CAMPBELL, Party Chief with the Geophysical Research Corporation, is located at 2416 Arbor Street, Houston, Texas.

JOHN C. HOFFMAN, Party Chief with the United Geophysical Company, should be addressed at 1255 East Green Street, Pasadena, California.

F. E. CURNUTT returned from South American employment several months ago, and is now located at P. O. Box 11, Kentwood, Louisiana.

Bulletin No. 14 of the U. S. Waterways Experiment Station Soil Mechanics Bulletin contains an abstract of the English translation of "Relations Between the Behavior of Clay Minerals with Respect to Water and the Physical Properties of Cohesive Soils," by K. Endell, W. Loos, H. Meischeider, and V. Berg. A copy is on hand at Society headquarters.

FRANCIS A. ROBERTS, of the Carter Oil Company, is located at P. O. Box 349, Hazlehurst, Mississippi.

Offices of the Mott-Smith Corporation have been moved from 909 Shell Building, Houston, Texas, to 1041 Mellie Esperson Building.

LOUIS STATHAM has left the Humble Oil and Refining Company to accept a position as Physicist at the University of California. His address is 921 Harbor View Drive, San Diego, California.

H. C. REICHERT should be addressed c/o Isaac A. Manning, Barranquilla, Colombia, S. A.

O. C. OLSON has accepted a position with the Oil and Gas Division of the Texas Railroad Commission as a Petroleum Engineer. He is located at Brady, Texas.

M. M. SLOTNICK, former Editor of GEOPHYSICS under whom this department was started, has reported for duty at the Naval Ordnance Laboratory in Washington, D. C.

S. C. STONEHAM, Party Chief with Geophysical Service, Inc., is now located at 2407 Jefferson Park Avenue, Charlottesville, Virginia.

MAURICE SKLAR, of the Shell Oil Company, Inc., has been transferred from Big Lake to Box 566, Pearsall, Texas.

LAWRENCE A. GOEBEL, of the Carter Oil Company, has been transferred from Decatur, Illinois, to P. O. Box 548, Ferriday, Louisiana.

WESLEY, J. RICKEL is acting as Observer with the Geophysical Research Corporation, Box 2040, Tulsa, Oklahoma.

LT. LEONARD F. UHRIG is serving with the Maintenance Battalion, 5th A. D., at Camp Cooke, Lompoc, California.

T. J. O'DONNELL of the Gulf Research and Development Company, is located at P. O. Box 733, Laurel, Mississippi.

CHARLES E. HOUSTON has left the Humble Oil and Refining Company to accept a full-time position in the Department of Physics of the University of Houston, Houston, Texas.

S. ZIMERMAN, of the Carter Oil Company, has been transferred from Jackson, Mississippi, to Box 441, Hope, Arkansas.

THE SOCIETY OF EXPLORATION GEOPHYSICISTS
CONSTITUTION AND BY-LAWS
(As amended to April, 1942)

I. Name

This Association shall be called the "Society of Exploration Geophysicists."

II. Object

The object of this Association is to promote the science of geophysics especially as it applies to exploration.

III. Membership

A—Members

1. Any geophysicist of recognized standing shall be eligible to membership, whether or not he is engaged in petroleum geophysics or in geophysical prospecting.
2. Any physicist, mathematician, geologist, or engineer of recognized standing who is investigating a geophysical problem or problems shall be eligible to membership.
3. Any geologist of recognized standing who is not a geophysicist of recognized standing, but who is acting as chief, or division chief in charge of geophysical surveying, shall be eligible to membership.

B—Associates

1. Any geophysicist, geologist, engineer, mathematician, or physicist who is a graduate of an institution of recognized scientific standing who is engaged in geophysics and who is not eligible to membership shall be eligible to associate membership.
2. Any person who is not a graduate of an institution of recognized scientific standing and who is not eligible to membership and who has shown ability in a routine phase of geophysical work and who is in a position of responsibility in geophysical surveying shall be eligible to associate membership.
3. Any representative or employee of a firm or corporation engaged in supplying equipment or supplies to the geophysical prospecting industry, provided such individual is the graduate of an institution of recognized scientific standing, or provided otherwise that such individual is qualified by adequate technical experience, shall be eligible to associate membership.
4. Associate members shall be known as associates.
5. Associates shall enjoy all the privileges of membership in the Society, save that they shall not hold office, sign applications for membership, or vote; neither shall they have the privilege of advertising their affiliation with the Society in professional cards or professional reports or otherwise.
6. The Executive Committee may advance to active membership, without the formality of application for such change, those associates who have, subsequent to election, fulfilled the requirements for active membership.

C—Student Members

1. Any graduate or undergraduate student in residence at a recognized university or college shall be eligible for student membership.
2. Student membership shall terminate one year after a student member ceases to be enrolled at a recognized university or college.

3. The privileges of student members shall be the same as those of associate members.

D—Election to Membership

1. Every candidate for admission as a member or associate shall submit a formal application on an application form authorized by the Executive Committee, signed by him, and endorsed by not less than three members who are in good standing, stating his training and experience and such other facts as the Executive Committee shall from time to time prescribe. Provided the Executive Committee, after due consideration, shall judge that the applicant's qualifications meet the requirements of the Constitution, they shall cause to be published in an appropriate publication the applicant's name and the names of his sponsors. If, after at least thirty days have elapsed since such publication, no reason is presented why the applicant should not be admitted, he shall be deemed eligible to membership or to associate membership, as the case may be, and shall be notified of his election. Provided the Executive Committee may accept applicants for either class of membership, who, because of their geographical location or because of their lack of acquaintance with active members of this Society, are unable to secure qualified sponsors, but who otherwise are eligible for membership. Applicants for student membership may be accepted as student members upon recommendation of a faculty member of the school they are attending, and with the unanimous approval of the Executive Committee.
2. An applicant for membership, on being notified of his election in writing, shall pay full membership dues for the current year and on making such payment shall be entitled to receive the regular Society publications for that year. Unless payment of dues is made within thirty (30) days by those living within the continental United States and within ninety (90) days by those living elsewhere, after notice has been mailed of his election, the Executive Committee may rescind the election of the applicant. Upon payment of dues, each applicant for membership shall be furnished with a membership card for the current year and until such written notice and card are received, he shall in no way be considered a member of the Society.

E—Honorary Members

1. The Executive Committee may from time to time and by unanimous action elect as honorary members persons who have contributed distinguished service to the cause of geophysics. Honorary members shall not be required to pay dues.

F—Code of Ethics

1. Membership of any class shall be contingent upon conformance with the established principles of professional ethics.

IV

A—Resignation—Suspension—Expulsion

1. Any member or associate may resign from the Society at any time. Such resignation shall be in writing and shall be accepted by the Executive Committee, subject to the payment of all outstanding dues and obligations of the resigning member or associate.
2. Any member or associate who is more than one year delinquent (in arrears) in payment of dues shall be suspended from the Society. Any delinquent or

suspended member or associate, at his own option, may request in writing that he be dropped from the Society and such request shall be granted by the Executive Committee. Any member or associate more than two years in arrears shall be dropped from the Society. The time of payment of delinquent dues for either one year or two years may be extended by unanimous vote of the Executive Committee.

3. Any member or associate who resigns or who is dropped under the provisions of Sections 1 and 2 of this article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.
4. Any person who has ceased to be a member or associate under Section 1 or Section 2 of this article may be re-instated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member or associate of the Society.
5. Any member or associate who, after being granted a hearing by the Executive Committee, shall be found guilty of a violation of the code of ethics of this Society or shall be found guilty of a violation of the established principles of professional ethics or shall be found guilty of having made a false or misleading statement in his application for membership in the Society, shall be asked to resign from the Society by unanimous vote of the Executive Committee. The decision of the Executive Committee in all matters pertaining to the interpretation and execution of the provisions of this section shall be final.

V. Officers and Their Duties

A—Officers

1. The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. These, together with the Past President, shall constitute the Executive Committee and managers of the Society. Officers shall be elected for a term of one year with the exception of the Editor, who shall be elected for a term of three years.
2. A ticket of nominations for officers and representatives shall be prepared by a Committee on Nominations which shall consist of the President and the two qualified Past Presidents in order of precedence. Favorable action of this Committee shall be two out of three votes. This Committee shall nominate two candidates for President, one of whom shall be the retiring Vice-President, and two candidates for each of the other offices to be filled.

   The ticket prepared by the Nominating Committee, as well as any other ticket presented in writing and signed by at least twenty members in good standing, shall be submitted to the President by November 30. The President shall secure written acceptance of nominations from each candidate. The names of nominees shall be placed on the official ballot which shall be mailed to each member not later than December 15. Names of candidates shall be listed alphabetically except that the name of the retiring Vice-President shall occupy first place cn the ticket. Blank spaces shall be provided on the ballot for writing in nominations for each office.

   Each member shall cast one vote for each officer to be elected and shall return his ballot to the Secretary-Treasurer. Ballots to be valid must be enclosed in an envelope carrying on the outside the written signature of the member submitting

the ballot, and must be received by the Secretary-Treasurer at his officially recognized address not later than ten days prior to the Annual Meeting. Only ballots received from members in good standing as of a date ten days prior to the Annual Meeting shall be valid. The Secretary-Treasurer shall indicate which ballots are valid by initialing the enclosing envelope and shall deliver the ballots unopened to the Nominating Committee for counting.

The Nominating Committee shall count the ballots immediately before the Annual Business Meeting. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Nominating Committee shall decide by a secret vote which of the candidates tied shall be elected.

The announcement of the election shall be made as the first of the new business considered at the Annual Meeting.

3. No one shall hold the office of President for two consecutive years and no one shall hold any other office for more than two consecutive years except that of Editor.

B—Duties of Officers

1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such committees as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee.
2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President in case of the absence or disability of the latter. He shall also act as Chairman of the Program and Arrangements Committee of the Society.
3. The Secretary-Treasurer shall assume the duties of the President in case of the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the recognized organ of the Society. He shall receive all funds of the Society and, under the direction of the Executive Committee, shall disburse all funds of the Society. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Executive Committee and the expense shall be borne by the Society. The funds of the Society shall be disbursed by check as authorized by the Executive Committee.
4. The Editor shall be in charge of the editorial business, shall submit an annual report of such business, shall have authority to solicit papers and material for the regular Society publication and for special publications, and may accept or reject material offered for publication. He may appoint associate, regional, and special editors.
5. In the event of absence, disability or resignation of any member of the Executive Committee, the vacant place in the Committee shall be automatically filled by

the next preceding qualified Past President who shall be known as Prior Past President.

6. The officers shall assume the duties of their respective offices immediately after the Annual Meeting following their election.

VI. Executive Committee—Meetings and Duties

A—Executive Committee

1. The Executive Committee shall consist of the President, Past President, Vice-President, Secretary-Treasurer, and Editor.

B—Meetings and Duties

1. The Executive Committee shall meet preceding the annual meeting and at the call of the President may hold meetings when and where thought advisable, to conduct the affairs of the Society. A joint meeting of the outgoing and incoming Executive Committees shall be held immediately after the close of the annual Society business meeting. Members of the Executive Committee may vote by proxy, mail or person on all matters which call for favorable or unanimous action.
2. The Executive Committee shall consider all nominations for membership and pass on the qualifications of the applicants, shall have control and management of the affairs and funds of the Society, shall determine the manner of publication, and shall designate the place of the annual meeting. They are empowered to establish a business headquarters for the Society, and to employ such persons as are needed to conduct the business of the Society. They are empowered to make investments of both general and special funds of the Society. Trust funds may be created giving to the trustees appointed for such purpose such discretion as to investments as seems desirable to the Executive Committee to accomplish any of its objects and purposes, but no such trust funds shall be created unless they are revocable upon ninety (90) days' notice. Favorable action shall consist of a favoring three out of five votes. Committee members may vote by person, proxy or in writing.

VII

A—Meetings

1. The Society shall hold at least one stated meeting each year, which shall be the annual meeting. This meeting shall be held at a time and place designated by the Executive Committee. At this meeting the proceedings of the preceding meeting shall be read, Society business shall be transacted, scientific papers shall be read and discussed, and results announced of the mail ballot for officers for the ensuing year.

VIII

A—Amendments

1. Amendments to this Constitution may be proposed by a resolution of the Executive Committee, by a Constitutional Committee appointed by the President, or in writing by any ten members of the Society. All such resolutions or proposals must be submitted at the annual meeting of the Business Committee of the Society as provided in the By-Laws, and only the Business Committee shall make recommendations concerning proposed constitutional changes at the annual

Society business meeting. If such recommendations by the Business Committee shall be favorably acted on at the annual Society business meeting, the Secretary-Treasurer shall arrange for a ballot of the membership by mail within thirty (30) days after said annual Society business meeting, and a majority vote of the ballots received within ninety (90) days of their mailing shall be sufficient to amend. The legality of all amendments must be determined by the Executive Committee prior to balloting.

B—Parliamentary Regulations

1. The rules contained in "Robert's Rules of Order, Revised" shall govern the Society in all cases to which they are applicable, and in which they are not inconsistent with the By-Laws or the special rules of order of this Society.

BY-LAWS

I

A—Dues

1. The fiscal year of the Society shall correspond with the calendar year.
2. The annual dues of members of the Society shall be five dollars ($5.00). The annual dues of associates for not to exceed six years after election shall be four dollars ($4.00); thereafter, the annual dues of such associates shall be five dollars ($5.00). The annual dues of student members shall be three dollars ($3.00). The annual dues are payable in advance on the first day of each calendar year. A bill shall be mailed to each member, associate, and student member before January first of each year, stating the amount of the annual dues and the penalty and conditions for default in payment. Members, associates, or student members who shall fail to pay their annual dues by March fifteenth shall not receive further copies of the regular Society publication, shall not be eligible to vote, nor shall they be privileged to buy Society special publications at prices made to the membership, until such arrears are met.

II

A—Publications

1. The proceedings of the annual meeting, the Constitution and By-Laws, and the papers presented at such meeting shall be published at the discretion of the Executive Committee in the regular publication or in such other form as the Executive Committee may decide best meets the needs of the membership of the Society.
2. The payment of annual dues for any fiscal year entitles the member or associate to receive without further charge the regular publication of the Society for that year. $3.00 ($3.50 foreign) of the annual dues is set aside for payment of the annual subscription to the Society Journal, GEOPHYSICS.
3. The Executive Committee may authorize the printing of special publications to be financed by the Society from its general, publication or special funds and offered for sale to members and associates in good standing at not less than the cost of publication and distribution.

III

A—Regional Sections, Technical Divisions, and Affiliated Societies

1. Regional sections of the Society may be established provided the members of

such sections are members of the Society and shall perfect an organization and make application to the Executive Committee. The Executive Committee shall submit the application for action first by the Business Committee and second to the Society for a letter ballot as for a constitutional amendment, and provided that the Society may revoke the charter of any regional section by similar action.

2. The Executive Committee may arrange for the affiliation with the Society of duly organized groups or societies, which by object, aims, constitution, by-laws, or practice are developing the study of geophysics or petroleum technology. In like manner, the Executive Committee may arrange conditions for dissolution of such affiliations. Affiliation with the Society need not prevent affiliation with other scientific societies. Members of affiliated societies who are not members of the Society, shall not have the privilege of advertising their affiliation with the Society on professional cards or otherwise, but shall be entitled to receive the regular publication of the Society upon payment of a fee equivalent to that charged an associate member.

IV

A—District Representatives

1. The Executive Committee may cause to be elected district representatives from districts which it shall define by a local geographic grouping of the membership. Such districts shall be redesignated and redefined by the Executive Committee as often as seems advisable. Each district shall be entitled to one representative for each seventy-five members, but this shall not deprive any designated district of at least one representative. The representatives so apportioned shall be chosen from the membership of the district by a written ballot arranged by the Executive Committee. They shall hold office for two years, their term of office expiring at the close of the annual meeting. In so far as possible, these two-year terms shall be overlapping.

V

A—Business Committee

1. The Executive Committee may institute a Business Committee to act as a council and advisory board to the Executive Committee and the Society. This Committee shall consist of the Executive Committee, the Prior Past President, and the district representatives. Favorable action by the Business Committee shall consist of a favorable two-thirds vote. The Secretary-Treasurer shall act as Secretary of the business meeting. Members of this Committee may vote in person, by proxy, or in writing. The Business Committee shall meet the day before the annual meeting at which time proposed changes in the Constitution or By-Laws may be considered, all old and new business shall be discussed, and recommendations may be voted for presentation at the annual meeting.

VI

A—Amendments

1. These by-laws may be amended by favorable vote of the Business Committee, providing that such changes have been recommended and legality approved by the Executive Committee. Such amendments shall be published in the next regular number of the recognized organ of the Society.

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MEMBERSHIP LIST BY GEOGRAPHICAL LOCATIONS

UNITED STATES

ALABAMA

Mobile
Meitzen, J. B.

ARKANSAS

Hope
Zimerman, Sam

Little Rock
Malamphy, Mark C.
Martin, Walter E.

Pine Bluff
Rusler, George W.

Stamps
Hubner, B. G., Jr.

Yellville
Roark, James J.

ARIZONA

Tucson
Pranglin, Lt. John A.

CALIFORNIA

Altadena
Judson, J. F.
Woods, R. E.

Bakersfield
Barling, Robt.
Dana, Drexler
Deming, J. H.
Dennis, Terence E.
Fleishman, Lt. Sam
Gaby, Phil P.
Ittner, Frank
Le Conte, Joseph
Mathews, John W.
Reel, C. E.
Saunders, L. W.
Thomsen, Harry L.
Trombla, L. B.

Burbank
Gayman, W. H.
Selby, Ernest R.
Wilson, Gardner P.

Fresno
Baird, Walter D.
Clement, Paul F.
Ferber, Herbert J.
Moran, R. B., Jr.
Northcutt, W. C.
Pezdek, Victor J.
Stones, J. Eugene

Glendale
Dodd, Lavon C.
Legge, J. A., Jr.
Waterfall, Louis N.

Hollywood
Sweet, Elliott

Lompoc
Uhrig, Lt. L. F.

Long Beach
Henquet, R.

Los Angeles
Batchelder, Dean E.
Benke, M.
Boccalery, Michael A.
Clark, R. W.
Desmond, Jack M.
Dresbach, C. H.
Ellsworth, T. P.
English, Walter A.
Gabriel, V. G.
Gilmore, H.
Maxwell, Joseph M.
McCloskey, Downs
McGrady, Dupree
North, Willard
Price, Wiley R., Jr.
Salvatori, Henry
Scharf, David
Shade, N. R.
Tracy, W. H.
Vallat, E. H.
Walling, Dean

Merced
Augenthaler, R. L.

Modesto
Cooper, B. B.
Heggblom, J. C.
Ramsay, William W.

Monterey Park
Rock, Sibyl M.

Pasadena
Benioff, Hugo
Christie, Norman J.
Denning, Wayne H.
Dix, C. Hewitt
Gutenberg, Beno
Harding, Maynard W.
Hoffman, John C.
Hoover, Herbert, Jr.
Loring, Ralph C.
Mansfield, Robert H.
Morris, Lawrence K.
Rupnik, J. Joseph
Sorge, Barthold W.
Soske, Joshua L.
Thornburgh, H. R.
Washburn, H. W.
Widess, M. B.

Riverside
Hull, J. W.

San Bernardino
Eichelberger, Martin, Jr.

San Diego
Brown, Leon D., Jr.
Johnston, T. F.
Mason, Jack
Peterson, Raymond A.
Statham, Louis
Urick, R. J.

San Francisco
Hillis, Donuil
Wheaton, G. S.

San Gabriel
Acker, Ralph F.

Santa Monica
Johnson, Curtis H.

South Pasadena
McKanna, Edwin A.
Nomann, Arthur B.
Stick, John C., Jr.

Tulare
Hall, Hubert N.

Whittier
Lynton, Edward D.
Moore, Horace S.

COLORADO

Boulder
Baird, John

Denver
Ballard, James A.
Boos, C. Maynard
Cox, Charles B.
Johnson, L. H.
Manning, A. B.
McCready, H. J.
Rugg, Allen M., Jr.
Wells, William M.
Wolters, Earl M.

Ft. Collins
Stommel, Harrison E.

Ft. Logan
McLemore, Ethel Ward

Golden
Heiland, C. A.
Levings, W. S.

Tripp, R. Maurice
Wantland, Dart

Louisville
Pellillo, M. J.

DELAWARE

Wilmington
Budd, Montgomery R.
Kelly, Sherwin F.
Smith, G. H.

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Lash, Charles C.

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Gould, Martin J.
Hedeman, W. R., Jr.
Hersey, J. B.
Hoffman, Malvin G.
Howell, Lynn G.
Hughes, Darrell S.
Jacques, Alvin T.
Kaiser, Capt. George B.
Kendall, James M.
Kennedy, Kenneth K.
McGhee, George C.
Mott-Smith, M. C.
Myers, John R.
Prade, Nat H.
Slotnick, M. M.
Smith, R. Ellis
Van Orstrand, C. E.

FLORIDA

Coral Gables
Blanchard, William G.

Tampa
Nash, Capt. John M.

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Koenig, Palmer E.
Ludwick, C. C.
Oudt, F W
Woodward, R. V.

Chicago
Bench, B. M.
Cram, Ira H.
Parkhurst, George L.

Glencoe
McAllen, W. J.

Marshall
Konkel, Philip M.

Mattoon
Stratton, Everett F.

Mt. Vernon
Rutherford, H.

INDIANA

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Davies, Nathan C.
Horton, H. M.

KANSAS

Barnard
Tucker, Paul M.

Hutchinson
Johnson, E. W.

Lawrence
Jakosky, J. J.
Wilson, Clyde H.

Pratt
Thomas, J. W., Jr.

St. John
Brewer, Ralph R., Jr.
Henderson, Paul V.

LOUISIANA

Alexandria
Watson, R. A.

Crowley
Egan, Daniel G.

Houma
Hamilton, W. Brooke
Hodgson, John H.
Hotard, A. A.

Kentwood
Curnutt, F. E.

Lafayette
Foster, Edward S., Jr.

Natchitoches
Manes, O. B.

New Iberia
Buck, R. D.

New Orleans
Brown, L. I.
Gaby, Ewin D.
Hoover, J. W.
Kretz, Robert L.
Lindsey, R. W.
Nichols, E. Turnley
Smith, Neal J.
Wiley, W. B.

Shreveport
Barret, William M.
Buchner, Harry M.
Caster, E. L.
Crain, Ashton
Donnelly, V. T.
Freeman, L. I.
Goebel, Lawrence A.
Horn, J. W.
House, H. M.
Lea, W. T.
Lowe, C. R.
McLaren, R. L.
Spencer, Leslie C.
Taylor, John E.
Wilson, Richard M.

Sulphur
Moore, James A.

University
Roy, Chalmer J.

MARYLAND

Edgewood Arsenal
Bliss, Robert, Jr.
Hale, Major Donald H

MASSACHUSETTS

Belmont
Garrett, George A.
Woodward, R. H.

Cambridge
Maxwell, E.
White, W. T.

Cape Cod
Haskell, Norman A.

Lincoln
Beers, Roland F.

Woods Hole
Crary, Albert P.
Ewing, Maurice

MISSISSIPPI

Hattiesburg
Dreyfus, Robert M.

Hazlehurst
Gallaway, Roy Lee
Roberts, Francis A.

Jackson
Fischer, L. F.

Laurel
O'Donnell, Thomas J.
Reed, Paul C.

Leland
Cooke, John G., Jr.

West Point
Strange, Booth B.

MISSOURI

Joplin
Latimer, M. W.
Seyffert, Willis A.

Kansas City
Carlson, Joe E.

St. Louis
Macelwane, Rev. James B., S. J.
Stearn, Noel H.

NEW JERSEY

Elizabeth
Jameson, M. H.

Ft. Monmouth
Hostetler, Lt. G. W.

Gibbstown
Burrows, Lawton A.

North Plainfield
Aiken, Charles B.

NEW MEXICO

Carlsbad
Kearns, B. E.

NEW YORK

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Myers, Clay K.

Garden City
Doolittle, Russell C.
Peoples, J. A., Jr.
Zenor, H. M.

Hempstead
White, Gifford E.
Witt, M. K., Jr.

New York
Church, Joseph H.
Gibbon, H. A.
Hardy, Willis W.
Hubbard, Bela
Moorman, H. R.
Olson, W. S.
Skeels, D. C.
Slichter, Louis B.
Weichert, R. F., Jr.
Whiton, Herman F.
Winkler, B. O.
Zavoico, Basil B.

Rochester
Tompkins, Frederick A.

Wellsville
Young, Wilbur H., Jr.

OHIO

Dayton
Kearby, Capt. J. G.

OKLAHOMA

Bartlesville
Beck, August F.
Courtier, William H.
Dietert, Arthur E.
Dissler, Ernest
Doan, Richard L.
Ericson, Harry B.
Haig, Ardris
Hintze, A. J.
Kidd, Robert L.
Piety, R. G.

Chicka sha
Allon, Michael
DeGood, R. G.

Cushing
Smith, Louis J.

Duncan
Elam, Daniel F.

Ft. Sill
Dickey, Calvin A. L.
Imle, Harry R.

Norman
Cady, Francis H.
Howard, G. C.
Lynn, Ralph D.
Schriever, William

Oklahoma City
McMullin, Lt. E. F.
Schaeffer, Hugh C.
Winter, A. B.

Ponca City
Athy, L. F.
Beeth, Donald
Crawford, John M.
Erickson, Anton
Haber, A. F.
Handley, E. J.
Hughes, Roland F.
Jordan, C. K.
Mount, E. L.
Prescott, H. R.
Searcy, Frank
Shepherd, C. Kenneth
Swan, Bird G.
Vorheis, Byron
Warren, Paul R.
Whitehead, L. E.

Seminole
Mercier, Vincent J.

Shawnee
Lukens, John P.

Tulsa
Anderson, O. W.
Barthelmes, Albert J.
Bazhaw, W. O.
Becker, H. C.
Bible, John L.
Bills, Robert N.
Bishop, F. L.
Blight, Richard E.
Borman, Frank W.
Born, Milton C.
Born, W. T.
Boucher, F. G.
Bryan, A. B.
Buffum, C. E.
Bullock, Robert L.
Burg, Kenneth E.
Burton, R. H.
Clark, R. C.
Coffin, R. Clare
Cooper, Jack R.
Craig, Robert L.
Dahlberg, Robert S., Jr.
Davenport, Robert
Day, Charles E.
Dyk, Karl
Eisler, Joseph D.
Emanuel, Vincent
Emrick, D. G.
England, C. M.
Faust, L. Y.
Ferguson, John L.
Flournoy, Murray B.
Gemmer, R. W.
Gilliam, J. T.
Gilliland, J. R.
Gilmour, Andrew
Green, W. G.
Harlton, Bruce H.
Hawkins, J. E.
Hopkins, James S.
Hurry, Clare N.
Innes, Arland I.
Jeffers, Paul H.
Kendall, G. D.
Kendall, W. B.
Lawrence, K. M.
Leedy, F. B.
Lester, O. C., Jr.
Long, Clarence J.
Manhart, T. A.
Marsh, Samuel R.
Martin, Dick
McGinity, J. V.
McNatt, E. M.
Miller, Vincent
Owen, J. E.
Perry, W. B.
Peters, Leo J.
Rankin, C. T.
Richardson, J. W.
Rickel, Wesley K.
Ricker, Norman
Riess, Malcolm
Ross, Charles M.
Rutledge, Richard B.
Seager, O. A.
Seaman, L. O.
Sexton, Louis P.
Sharpe, Joseph A.
Sibley, W. B.
Silverman, Daniel
Smith, Noyes D.
Sparks, Neil R.
Strachan, Clyde G.
Swearingen, A. C.
Teague, Norman P.
Taylor, Albert

Teague, Norman P.
Thomsen, Erik
Thralls, H. M.
Van Croy, Stefan
Van Valkenburgh, J. C.
Vernon, Jess
Wagoner, George E.
Walton, George G.
Watson, Robert J.
Weatherby, B. B.
West, S. Stewart
Westby, G. H.
Wilcox, Stanley W.
Williams, P. S.
Willis, Floyd, Jr.
Winn, Clayton N.
Winnek, J. R.
Wise, L. H.

OREGON

Portland
Williston, Samuel H.

PENNSYLVANIA

Bethlehem
Agocs, William B.

Philadelphia
Bazzoni, Charles B.

Pittsburgh
Affleck, James
Allen, Frank T.
Backman, John E.
Bailey, Lothrop H.
Boots, Paul H.
Bradford, Donald C.
Bryan, Carl L.
Butler, Mark D.
Butler, W. W.
Caldwell, C. L.
Cerveny, Philip F.
Cook, D. E.
Copeland, R. J.
DeWoody, D. A.
Diveley, Paul R.
Dobrin, Milton B.
Dombart, William F.
Eckhardt, E. A.
Elkins, Thomas A.
Ferrick, James H.
Gardner, Louis W.
Gealy, Wendell B.
Gemmell, Howard F.
Gunn, J. E.
Hammer, Sigmund I.
Hastings, W. K.
Herron, Robert C.
Hollobaugh, Robert C.
Jones, Ralph E.
Kerbow, R. B.
Lee, Walter B., Jr.
McCracken, Guy I.
McGee, John E.
Meyer, Edgar J.
Muffly, Gary
Muskat, Morris
Nettleton, L. L.
Palmer, E. M.
Palmer, Loyal D.
Perkins, B., Jr.
Reiser, Robert G.
Ritzmann, O. F.
Robinson, John L., Jr.
Robinson, W. Bernard
Ross, R. B.
Scott, D. L.
Sessions, Sanson S.
Smith, Douglas H.
Staples, Guy W.
Swartz, Charles A.
Texter, John W.
Tomlinson, John B.
Vacquier, Victor
Watson, George R.
Weber, David M.
Wert, Carl M.
Westrick, Edmond W.
Woodard, D. H.
Wyckoff, Ralph D.

State College
Pirson, Sylvain J.

Wilkinsburg
Morrison, M. S.

TENNESSEE

Lebanon
Agee, F. H.

TEXAS

Abilene
Hale, C. Russell

Alvin
Steele, Lt. W. E., Jr.

Amarillo
Richards, Billy E.

Athens
Smitherman, Lynn A.

Austin
Hargis, A. V.
Konz, Leo W.
Romberg, Frederick E.

Bellaire
Wolf, Alexander

Beaumont
Blocher, Charles L. M.
Ellis, L. G.
Hollingsworth, W. E.
Nahas, Capt. John M.
Rose, H. W.
Shafer, Russell E.
Smiley, W. G., Jr.

Brady
Olson, O. C.

Brownfield
Dana, R. H.

Camp Bowie
Bates, Cpl. Charles C.
Batson, Lt. James B.

Camp Hulen
Moody, Capt. Herbert H.

Clarksville
Itten, Howard

Corpus Christi
Howerton, Bert P.

Dallas
Adams, Hal R.
Albright, E. G.
Augustat, George
Bevan, Thomas J.
Brown, H. Hallock
Browning, K. A.
Charske, C. J., Jr.
Clark, Charles Lindsey
Collingwood, D. M.
Cortes, Henry C.
Dahm, C. G.
Dexter, Laurence N.
Dobyns, D. R.
Doering, John
Doss, C. L.
Douglas, Norvel
Elms, R. G.
Farren, Paul
Fetzer, E. L.
Fisher, Barney
Gillin, John A.
Green, Cecil H.
Harkey, W. J.
Hieatt, Herbert F.
Hurt, W. B.
Jackson, Capt. Robert W.
Jasinski, Edward J.
Jett, J. E.
Jones, M. P.
Jonsson, J. E.
Karcher, John C.
Kelsey, Martin C.
Kennedy, Frank H., Jr.
Kiesler, Ernest A.
Lahee, Frederic H.
Lester, John A.
Lewis, Karl E.
Lovinggood, Toby
MacNaughton, Lewis W.
Mann, Neil W.
McBurney, Charles G.
McDermott, Eugene

Meade, George N.
Melton, Ben S.
Menefee, James C.
Minton, J. P.
Moon, Jake
Moore, Charles M.
Morrow, Dallas C.
Nash, Paul E.
Newton, W. W.
Paslay, L. C.
Pernell, J. H.
Perryman, J. D.
Pittman, C. V. A.
Poindexter, Louis
Pollard, J. C.
Pollei, Donald W.
Pratt, R. B.
Ransone, W. R.
Reagor, Edward C.
Renner, Darwin S.
Rice, E. R., Jr.
Rollins, J. Frank
Sargent, R. L.
Schley, Woodruff H.
Seifert, Wesley H.
Seiler, George E.
Shugart, T. R.
Smith, C. B.
Somers, George B.
Stanton, Austin N.
Storm, Alfred E.
Stulken, E. J.
Sullivant, George A.
Tabor, E. M.
Van Cleave, R. F.
Walczak, Michael J.
Waters, Kenneth H.
White, Rex H.
Williams, Charles C.
Williams, Floyd J.
Williams, Richard
Wilson, E. E.
Wooley, William C.
Zeigler, B. F.

Danbury

Garrett, William M.

Denison

Wood, Arthur B.

Ft. Sam Houston

McCartney, Reed L.
Neumann, G.
Stubbe, G.

Ft. Worth

Harris, Sidon
Hightower, C. H.
Ledyard, Paul H.
Lovejoy, J. B.
Morris, James L.
Sandidge, Irl, Jr.
Taylor, Garvin L.
Wilson, John H.

Frijole

Pratt, W. E.

Hamilton

Stiles, Elisabeth

Houston

Adler, Joseph L.
Antes, Leland L.
Arthur, Marion A.
Back, Denys H.
Bader, Glenn E.
Baker, Malcolm C.
Banta, H. E.
Barnette, L. Atmar M.
Bennett, Roy F.
Bertram, A. C.
Black, J. P.
Blau, L. W.
Blevins, David C., III
Bolinger, John W.
Bowsky, Merle C.
Bradley, R. M.
Brooks, James A., Jr.
Brooks, O. D.
Broussard, C. H.
Broussard, D. F.
Brown, Hart
Burnett, Arthur C.
Busch, H. W.
Byers, J. W.
Campbell, F. F.
Campbell, William R.
Carlton, Dave P.
Carr, G. W.
Cash, Harvey, Jr.
Child, V. E.
Clifford, O. C., Jr.
Cobb, Howard L.
Conrad, P. P.
Cowles, Laurence G.
Cox, Harris
Cross, J. W.
Crowell, J. H.
Culbertson, J. A.
Davis, Donald M.
Deussen, Alexander
Doll, H. G.
Donnally, Chester J.
Dunlap, A. D.
Duty, Robert S., Jr.
Eby, A. N.
Eby, J. Brian
Epperson, R. S.
Evjen, H. M.
Fain, Edgar A.
Falkenhagen, H. M.
Fecht, Arthur J.
Ferguson, J. G.
Ferris, Craig
Flude, J. W.
Fohs, F. Julius
Free l, J. F.
Frosch, Alex
Gahagan, Donald I.
Gallie, J. F.
Gardner, Derry H.
Garrett, L. P.
Gibson, M. O.
Gilmore, John A.
Golden, John M.
Goldstone, Frank
Gomez, J. S.
Goss, Henry V.
Griffin, I. M., Jr.
Guseman, L. F.
Hafner, W.
Hall, T. O.
Halliday, O. T.
Hamil, A. B.
Happel, Henry H.
Harkins, T. I.
Harrington, G. H.
Haynes, C. J.
Henderson, Homer I.
Heroy, William B.
Herzenberg, A. J.
Hibbler, Alfred J.
Hibbler, M. E.
Hillyer, Ray H.
Hoard, J. O.
Holmer, Ralph C.
Honnell, P. M.
Horton, Claude Wendell
Horvitz, Leo
Houghton, H. M.
Houston, Charles E.
Hunzicker, A. A.
Irby, W. L.
Ivy, John S.
Jackson, G. L.
Jackson, Ralph S.
Jerome, J. Glen
Judson, Sidney A.
Kannenstine, Fabian M.
Klipsch, Paul W.
Ladner, Albert L.
Lamb, George B.
Langley, R. M.
La Rue, James E.
La Rue, Wilton W.
Lawhorn, O. T.
Lay, Roy L.
Leonardon, E. G.
Lewis, William Bradley
Lipson, Edward
Lohse, John M.
MacAllister, C. T.
MacMahon, A. M.
Mannes, W. H.
Marr, John D.
Marti, J. E.

Martin, Sidney A., Jr.
McCollum, Burton
McCollum, Elton V.
McCullagh, John, Jr.
Merritt, H. W.
Miller, R. D.
Millet, M. J.
Mitchell, George D., Jr.
Montgomery, George P., Jr.
Moore, Arthur A., Jr.
Moore, Homer C.
Mott-Smith, L. M.
Mounce, W. D.
Mower, L. K.
Muzzey, David S., Jr.
Neff, W. D.
Neuman, L. J.
Nisle, Robert G.
O'Brien, Decatur
Osterhoudt, W. J.
Palmer, John E.
Palmer, R. L.
Patrick, H. G.
Peacock, H. B.
Ray, Robert H.
Reed, Charles F.
Reynolds, F. F.
Rolshausen, F. W.
Rossaire, E. E.
Rulfs, Gerard William, Jr.
Sanders, C. W.
Saville, W. G.
Schafer, Sidney
Scherb, Ivan V.
Schmidt, Henry
Schmuck, R. H.
Schoellhorn, Henry, III
Schofield, G. A.
Scholl, Louis A., Jr.
Schumacher, J. P.
Schwennesen, A. T.
Selig, A. L.
Shapard, Charles A.
Sherar, E. S.
Sherar, Stuart
Shore, H. F.
Siegel, Frank
Sims, Sam E.
Sisson, H. H.
Smith, Aylwin L.
Smith, J. Angelo
Stone, George B.
Sundt, O. F.
Taylor, Josiah
Taylor, W. Harlan
Terry, Melvin C.
Teufel, Virgil W.
Theis, R. H.
Thomas, J. W.
Thompson, R. R.
Treybig, B. H., Jr.
Urbom, O. W.
van Melle, F. A.
Van Weelden, A.
Walker, R. Y., Jr.
Wallace, C. R.
Walsh, T. N.
Watt, J. S.
Weatherby, S. P.
Weaver, Paul
Whitney, Paul A.
Williams, E. D.
Wilson, H. A.
Woods, J. P.
Yeates, F. L.
Zazvorka, Jerry, Jr.
Zimmerman, C. C.
Zirbel, N. N.

Lubbock
Head, E. I.
Kilborn, J. M.
Klaus, H.

Marshall
Lea, N. J.
Moose, Dale H.

Maypearl
Thomas, Earl

Midland
McKay, A. E.
Winter, Niles B.

Monahans
Paddison, Louis J.

Pearsall
Sklar, Maurice

Pecos
Ruhlen, W. W.

Randolph Field
Faris, Lt. J. P.

Riverside
Weinzierl, John F.

Rosenberg
Chandler, Lyman, Jr.

San Angelo
Unger, Earle E.

San Antonio
Allen, Thomas L.
Bevier, George M.
Crawford, Paul D.
Dahlberg, Jack K.
DeLoach, Edward L.
Howe, Ralph H.
Imle, John F.
Kelley, W. W.
Mayfield, W. I.
McAlister, C. H.
Moore, Marion J.
Moore, W. Lee, Jr.
Petty, Dabney E.
Petty, O. S.
Roberts, Homer E.
Souther, J. B.
Weisbrich, R. A.
Whitsitt, C. D.

Terrell
Carter, Ray K.

Texarkana
Hogg, W. B.

Three Rivers
Whitley, W. M.

Tulia
Graham, Burleson

Tyler
McCaleb, M. M.

VIRGINIA

Alexandria
Odenweller, Keith H.

Arlington
Morgan, Major Chas. Gill
Wenz, Gordon M.
Wetzel, W. W.

Charlottesville
Stoneham, S. C.

Fort Belvoir
Lambrecht, Forrest F.

WASHINGTON

Fort Lewis
Lambert, Lt. G. D.

WEST VIRGINIA

Princeton
Straley, H. W., III

WYOMING

Rawlins
Johnston, Frank M.

FOREIGN

ARGENTINA

Buenos Aires
Martin, Rodolfo
Ramaccioni, D.
Rozlosnik, Andres

BORNEO

Balikpapan
Brons, H. H.
De Blank, B.

Bandjermasin
Jackson, J. B.
Maliphant, H. C.

Tarakan
Schoorel, P. M.

BRAZIL

Rio de Janeiro
Amaral, I. C. do
Oddone, D. S.

CANADA

Alberta

Calgary
Bickel, Harold
Johnson, G. R.

British Columbia

Vancouver
Paterson, Lt. R. T.

New Brunswick

Moncton
Hole, H. W.

Ontario

Toronto
Berwick, J. D.
Lundberg, Hans
Milstein, Mark N.

CANAL ZONE

Cristobal
Lehman, Frank F

Diablo Heights
Carson, J. P.

COLOMBIA

Barranquilla
Reichert, H. C.
Williams, C. E.

Bogota
Bonillas, Ygnacio
del Rio, Alejandro M.
Etherington, Thomas J.
Hazen, George H.
Samuels, G. H., Jr.
Sawyer, J. H.
Waring, W. W.

El Centro
Acheson, C. H.

COSTA RICA

San Jose
Wallis, W. E.

CUBA

Guantanamo Bay
Ervin, Lt. Lynn

DOMINICAN REPUBLIC

Ciudad Trujillo
Arick, M. B.

ECUADOR

Guayaquil
Durham, Charles A.
Meador, Bernal M.
Mitchell, Fielding L.
Ward, Dwight E.

EGYPT

Cairo
Beresford, Robert
Haight, H. W.

ENGLAND

Cheshire
Germain-Jones, D. T.

London
Lake, J. L.
Richards, T. C.
Shaw, Herman

Notts
Davies, Richard

Surrey
Jones, John H.

FRANCE

Saint Gaudens
Schlumberger, Marcel

GERMANY

Berlin
Bentz, Alfred

Breslau
Mintrop, L.

Freiburg
Koenigsberger, J. G.

Hanover
Brinckmeier, Georg
Schleusener, A.

HAWAII

Oahu
Long, Capt. John V.

IRAQ

Basrah
Barnett, G. W. T.

JAVA

Batavia Centrum
Brown, Donald R.

MEXICO

Mexico City
Alvarez, Manuel, Jr.
Rojas, A. Garcia

Sonora
Brenner, Morris

NICARAGUA

Puerto Cabezas
Hoylman, H. Wayne

PERSIAN GULF

Bahrein Island
Barger, Thomas C.
Shuler, Ellis W., Jr.
Van Beveren, O. F.

PERU

Negritos
Alber, John L.

PHILIPPINE ISLANDS

Cavite
Mortlock, Frank O.

Manila
Ross, J. D.

ROUMANIA

Ploesti
Small, Walter M.

SUMATRA

Medan
Coit, R. B.

Palembang
Alexander, Warren A.
Penney, A. B.
Romberg, Marvin
Wessler, George H , Jr.

Pangkalan Brandan
de Pijper, T.
Postma, G. W.

Pladjoe
Jansen M., J. J. H.

Tandjoeng Loentar
de Bruyn, J. W.

SWITZERLAND

Zurich
Fisch, W.

TRINIDAD

Pointe-a-Pierre
Brotherhood, G. Roy
Higgins, G. E.

Port of Spain
Templeton, J. C.

UNION OF SOUTH AFRICA

Johannesburg
Weiss, Oscar

URUGUAY

Montevideo
Vercesi, Daniel Rey

VENEZUELA

Barcelona
Hatheway, Joseph G.
Meszaros, W. A.

Caracas
Franks, W. E.
Frost, Holloway
Gerdes, C. H.
Jones, J. Byron
Kaufmann, G. F.
Kamen-Kaye, M.
Kimble, Henry R.
Lee, B. D.
Luchsinger, F. C.
Merritt, W. C.
Mix, Adrian E.
Perkinson, Floyd

Caripito
Browning, Paul
Burney, James H.
Warrick, Thomas R.

Maracaibo
Barksdale, G. L.
Pickle, Chesley B.